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Three Essays on Taxation, Environment, and Welfare

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Three Essays on Taxation, Environment, and Welfare

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Dedication

To my family

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Three Essays on Taxation, Environment, and Welfare

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My dissertation examines theoretically the effects of environmental taxation on welfare in various cases. Using a general equilibrium model, the first chapter shows that a Pigouvian tax provides a larger welfare gain than an output tax, since it induces substitution among inputs as well as reduction in output of the dirty good, while an output tax induces only the output reduction. Using data for China and the U.S., numerical simulation results show that the potential welfare loss from not being able to use a Pigouvian tax is much larger in developing countries than in developed countries.

The second chapter focuses on the fact that recycled material needs reprocessing to be substitutable for virgin material. Reprocessing uses resources and, in the process, generates pollution. Incorporating these 'imperfect' characteristics into a simple general equilibrium model, I examine how these realistic factors affect the structure of tax-subsidy schemes when the Pigouvian taxes are not available. A generalized Deposit-Refund system can achieve the optimum if illegal dumping is not taxable. Without a Pigouvian tax on illegal dumping, recycling is subsidized for its role in diverting illegal

disposal into proper disposal. If Pigouvian taxes on neither illegal disposal nor waste from imperfect reprocessing are available, a combination of output tax on reprocessed material and subsidies for clean inputs can be used to restore the optimum. In the process, another reason to subsidize recycling emerges: recycling is a clean input for imperfect reprocessing.

The third chapter focuses on the validity of the results obtained in the first chapter in the case of two vertically-separated oligopolies where the upstream industry is polluting. Using an analytical partial equilibrium model, I show that a tax on pollution is potentially superior to a tax on intermediate good, since the former can utilize both the upstream firms' input substitutability and the downstream firms' input substitutability, while a tax on intermediate good only utilizes the downstream firms' input substitutability. I also derive the conditions that government can improve social welfare through various revenue-neutral tax reforms.

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Welfare Effects of the Environmental Taxes in Developing Countries

1.1 INTRODUCTION

Many developed countries have implemented various policy measures to protect and improve the quality of their environment. Recent studies (OECD, 1995; 1996) have identified major advantages to a greater use of 'economic instruments' (EIs) such as taxes or charges and tradable permits in environmental policy, compared to 'command and control' (CAC) approaches. However, EIs are heterogeneous policy tools. The textbook case of a Pigouvian tax is far from widely used, mainly due to the information requirements and other institutional constraints (McMorran and Nellor, 1994). The successful implementation of EIs might heavily depend on pre-existing institutional conditions (see, for example, Russell and Powell, 1996; Smith, 1997).

These institutional conditions are particularly unfavorable in developing countries. Existing regulations, usually fashioned after those in developed countries, have often proven unenforceable and impractical. The efforts required to cope with the design of these policies and institutional changes for launching EIs are additional burdens on those developing nations (Panayotou, 1991; Serôa da Motta, et al 1999). Developing countries also have other structural characteristics different from those of developed countries. They often use more polluting fuels such as coal and unleaded gasoline, engage in more-harmful and less-efficient consumption and production activities such as slash-and-burn farming in Brazil, and drive more polluting vehicles per mile traveled such as small scooters in many South Asian countries. Finally, they tend to have agricultural that are large and often under-taxed, polluting industries that account for a large proportion of total output, and high marginal environmental damages per unit of output.

This chapter examines how these constraints affect the welfare gain from the introduction of environmental taxes in developing countries. It uses a simple analytical general equilibrium model with three sectors: one taxable clean manufacturing sector, one polluting manufacturing sector, and one non-taxable clean sector that represents subsistence farming and/or small non-market production activities.

First, this chapter theoretically shows that an ideal Pigouvian tax provides larger welfare gain than an output tax. Leaving aside problems of monitoring or enforcement, a Pigouvian tax is an ideal instrument to internalize an environmental externality because it reduces consumption of the output as well as use of the dirty input. Since emissions themselves are often hard to measure, however, both developed and developing countries have often relied on the taxation of output of the polluting industry. Using the log-linearization technique, this chapter solves for the second-best optimal Pigouvian tax and output tax in the presence of a distortionary tax on market use of labor (or equivalently, a pre-existing consumption tax on all market goods).

Second, the model allows structural constraints to be incorporated and quantified through a set of parameter values rather than relies on anecdotal evidence that developing countries have experienced. The chapter uses data for China, which is believed to share many characteristics commonly observed in developing countries in a broad sense. Using the data for China, I calculate the net welfare effects of either using the ideal Pigouvian tax instead using an output tax. The numerical simulation results show that the net welfare gain from the use of a Pigouvian tax could be more than *four* times larger than that of an output tax. On the other hand, the welfare gain from using a Pigouvian tax is only 50 percent larger than that of an output tax in developed countries. Therefore, the potential welfare disadvantage from using output taxes for environmental purposes appears to be greater in developing countries. This potential welfare disadvantage implies that developing countries' efforts in various structural reforms have important effects on the welfare outcomes of their environmental policies. Moreover, the welfare disadvantage does not imply that developing countries should avoid using environmental output tax instruments. Although an introduction of an environmental output tax offers smaller welfare gain in developing countries than in developed countries, the welfare gain from output tax instruments might be substantial, considering the potential savings from monitoring and enforcement activities.

Section 1.2 briefly overviews past experiences with EIs, while Section 1.3 reviews the previous literature. In Section 1.4, I present the model and derive the optimal tax rates and net welfare expressions for both the emissions tax and output tax. Section 1.5 discusses the implications of these analytical results, while Section 1.6 presents simulation results. Section 1.7 concludes.

1.2 PAST EXPERIENCES WITH ECONOMIC INSTRUMENTS

The traditional and most direct approach to environmental management is to impose technology restrictions and guidelines, enforced using fines and fees. But this CAC method can be difficult and expensive to implement, monitor, and enforce. In the economic literature, the CAC approach has been deplored on grounds of both static and dynamic inefficiency, because it asks for the same level of compliance by all polluters despite differences in marginal abatement costs. Furthermore, it does not provide any incentives to polluters for technical improvement to reduce pollution in the future (Baumol and Oates, 1988; Cropper and Oates, 1992).

EIs include both taxes and permit systems, but the model in this chapter is based on perfect certainty and thus does not really distinguish between them. Since taxes and permits are equivalent, I refer only to Pigouvian taxes (fees or charges) and environmental output taxes.[1] A Pigouvian tax (or emissions tax) is a specific tax per unit of emissions. The optimal rate of tax is equal to the pollutant's social marginal environmental damage (MED) at the socially-efficient level of emissions (Pigou, 1932). In theory, Pigouvian taxes reduce pollution in the least-cost manner: they encourage polluters to determine the combination of lower output, substitution among inputs, and investment in new technology that reduces emissions at least cost.

On the other hand, taxes on output or purchased inputs might be used for environmental purposes, though they have traditionally been used mainly for revenue purposes.[2] In many cases, they are intended to encourage pollution abatement by taxing outputs or inputs whose use is *linked* to environmental damage, rather than taxing emissions directly. Unlike a Pigouvian tax, however, an output (or input) tax achieves a socially-efficient level of emissions in the least-cost manner *only if* the nature of the linkage between the tax base and the environmental damage is fixed. Without fixed linkage to pollution, they usually deliver only the output effect (Fullerton, et al, 2001). In other words, they do not provide incentives to abate emissions per unit of output;

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[1] Some studies (OECD, 1999b; Smith, 1997) divide environmental tax instruments into charges (or fees) and taxes based on whether they are requited or not. However, in this paper, I will use all these terms interchangeably.

[2] I will use "Pigouvian tax" for a tax per unit of emissions and "output tax" for a tax on output of the polluting industry. Therefore, by my definition, the most important characteristic in determining if any particular tax (or charge) belongs to the Pigouvian tax category depends on whether it directly hits the emissions themselves. If not, I will call it an output tax.

they only reduce consumption of goods and services produced using emissions.[3] Furthermore, they may affect other non-targeted activities (Eskeland and Jimenez, 1992).

Why are environmental output (or input) taxes so popular then? First of all, environmental output taxes are relatively easier to administer than ideal Pigouvian taxes. For design and implementation of a perfect Pigouvian tax, the environmental authorities would have to monitor the sources of pollutants continuously, enforce the potential polluters to comply, and decide the optimal rate of tax for each polluter. These administrative activities are by no means easy tasks, even in developed countries.[4] The situations in many developing countries are worse: their institutional weaknesses such as under-funding and inexperience tend even further to limit the effective implementation of Pigouvian taxes.[5] Furthermore, it is often difficult to introduce new environmental taxes. In comparison, output taxes are relatively easy to implement.[6] Many existing taxes are levied on the value of goods and services sold (or the value of incomes paid or received). For example, excise taxes on fuel and other energy products are probably the most widespread environmental taxes mainly because of their administrative convenience (OECD, 1999a).

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[3] For instance, a tax on coal intended to reduce sulfur emissions will also affect manufacturers that use coal to extract chemicals for dyeing. If a tax were imposed on the sulfur content of coal, the manufacturers in the dyeing industry would unnecessarily be induced to switch to lower-sulfur coal or to find other sources of chemicals (Blackman and Harrington, 2000).

[4] Political considerations or the practical problems of design and implementation such as who is to be taxed are often the most important factors that determine the types of policy tools employed (Barthold, 1994).

[5] This does not necessarily imply that environmental output taxes are free from such institutional constraints, only that such constraints may be smaller for an output tax.

[6] Smith (1996) points out that "where the assessment, collection, or enforcement of the tax can be 'piggy-backed' on to corresponding operations already established for existing taxes, the costs of an environmental tax measure may be significantly lower than where entirely-new administrative apparatus and procedures are required."

A comprehensive survey of the use of EIs (OECD, 1989) reports over 150 instances related to the purpose of environmental improvement in 14 OECD countries. However, many taxes and charges adopted partly for environmental reasons were mainly for the purpose of raising revenues. Other surveys show a rising trend in the use of EIs in developed countries. OECD (1994) reports the number of EIs increased almost 50 percent just from 1987 to 1991. Covering the years 1997-1999, OECD (1999b) shows that all of the OECD Member countries that responded to the questionnaire (24 out of 29) are using some types of EIs.

However, the popularity of EIs among developed countries often blurs the true nature of environmental instruments: many environmental taxes titled "emission charges or fees" usually are *not* exactly Pigouvian taxes. As Fullerton, et al (2001) emphasize, most charges on various pollutants are not Pigouvian taxes, no matter what they are called. Difficulties in precisely monitoring the levels of pollutants force many developed countries to use less-ambitious charges or taxes on the bases that are easier to observe and enforce (OECD, 1999a).

The situations in developing countries are not much different and might be worse.[7] Technological constraints such as the use of dated technologies are mixed with structural constraints such as large numbers of small polluters that are hard to regulate, large traditional sectors, high bureaucratic cost, corruption, lack of political will, and severe shortage of budget and manpower. All these factors make it more difficult to implement EIs successfully. In China, for example, emission fees are charged on 20

[7] In addition to the difficulties with monitoring and enforcement of effective environmental policy instruments, many developing countries have distinct structural characteristics different from developed countries. They are often characterized by a large share of agriculture in total output and employment, and by large share of informal (or non-taxable) economic activities (Tanzi and Zee, 2000). Due to these constraints, many developing countries have relied heavily on indirect consumption taxes such as sales or excise taxes. This paper takes advantage of the fact that a uniform consumption tax on market output is equivalent to a uniform tax on market labor.

different air pollutants. However, firms are required to pay fees only for the 'worst case pollutant,' even when more than one pollutant exceeds the permissible level. Other pollutants face *no* charge at the margin.[8] Worsening these problems is that fees reduce firms' tax liabilities, and that 80 percent of fees are eventually returned to these firms. These problems cause perverse incentives for firms to perpetuate noncompliance (Blackman and Harrington, 2000).[9]

1.3 LITERATURE REVIEW

Though the literature on environmental taxes is vast, it usually assumes that emissions can be perfectly observable, or that a tax on the consumption good or a tax on a market input corresponds exactly to a tax on emissions. An early example is Sandmo (1975). He examines the optimal tax rate when the aggregate amount of one of the consumption goods enters the utility function directly as a negative externality. Thus, he assumes that the relation between the output and the externality is fixed, where only changes in output level can reduce the emissions level. In this case, a tax on emissions is equivalent to a tax on the output of the polluting industry.

Cremer and Gahvari (2001) re-examine the results of Sandmo in the case where taxation of a consumption good is not equivalent to a tax on emissions. In a second-best world with distorting labor taxes, they show that taxes on emissions and on

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[8] Furthermore, actual monitoring of emissions is based only on visual inspection of the clarity of flue gases. Actual fees are determined in combination with estimates of emissions volumes, but many studies point out that the emissions fees are well below marginal abatement costs for most firms and thus provide limited abatement incentives (Yang, et al, 1997).

[9] In order to solve administrative difficulties in implementing an emissions tax, developing countries often rely on other policy instruments: product taxes on fuels in many countries, voluntary agreements and information disclosure such as the Clean River Program in Indonesia (O'Connor, 1998). However, the overall evaluation of experiences with EIs in many developing countries indicates that EIs have potentially increased technical and financial burdens on already-fragile institutional structures (Serôa da Motta, et al, 1999; McMorran and Nellor, 1994).

consumption goods can be set separately to address different objectives: an emission tax solves the externality problem while output taxes are determined in conformity with optimal tax considerations. However, they do not examine the magnitude of possible welfare losses from using an output tax instead of an emissions tax, since they still assume that a firm's emission level is fully observable.

Cropper and Oates (1992) have suggested that output taxes may be superior to an emissions tax if monitoring is costly. Schmutzler and Goulder (1997) explicitly examine the importance of monitoring costs in the choice between taxes on emissions and taxes on outputs (or inputs). Under imperfect monitoring, they show that output taxes might be preferred to emissions taxes if outputs are easily substitutable and abatement options are scarce. Hoel (1998) also argues that emission taxes may be no more effective than other policies if abatement costs are uncertain and non-convex, and if measuring emissions is difficult.

Vatn (1998) approaches the problem in a different way. Using a material balance perspective in his model, he assumes that all economic activities such as extraction, production, and consumption generate emissions. Normally, it becomes harder and more expensive to detect and mitigate them in the later stages of economic activities, since emissions become part of numerous inputs and outputs. If transaction costs internalizing the externalities outweigh the gains from hitting the target more precisely by using an emissions tax, the use of input-oriented taxes might be more efficient.[10]

To compare alternative taxes, Fullerton, et al (2001) start by showing theoretically and numerically that the emissions tax raises welfare more than an output tax. They do not explicitly measure or model the costs of targeting the tax on pollution,

[10] Broadly speaking, transaction costs include monitoring, enforcement, and other controlling costs incurred by the environmental authorities.

such as the costs of measurement, monitoring, and enforcement, but their numerical simulation results show how big those costs must be to justify the use of the output tax instead. In a more direct comparison, Smulders and Vollebergh (2001) explore the trade-off between incentive effects and administrative costs associated with the implementation of various environmental tax instruments. They find that the output tax might be favored if emissions are closely linked to the uses of output, if other technological abatement methods are not plentiful, and if administrative costs of the emissions tax are high. Others argue that output or input taxes such as fuel taxes can be quite effective to control air pollution in developing countries if accompanied by emissions standards to stimulate cleaner technologies (Eskeland, 1995; Eskeland, et al, 1998).

1.4 THE MODEL

The developing country model has three production sectors: two taxable manufacturing sectors $(X \text{ and } Y)$ and one non-taxable subsistence agricultural sector (Z). This static model considers only one time period, with no saving decision. The N identical households obtain utility from the clean manufactured good (X), the dirty good (Y), the clean agricultural good (Z), a government-produced public good (G), and environmental quality (E).

The household allocates a fixed amount of time $\left(\bar{L}\right)$ between taxable labor (L) and non-taxable labor $\left(L_Z\right)$. For simplicity, I refer to the resource as time available for labor supply, but more generally, it can be a fixed total amount of all resources such as labor, capital, land, and energy. In that case, L can be interpreted as the resources used in the market, where L_Z is the amount used for subsistence agriculture. This reflects not only the conceptual problems in measuring agricultural income for taxation, but also administrative difficulties in monitoring and enforcement of that tax.[11] Therefore, I assume that Z is non-taxable.[12]

The clean good is produced with a constant returns to scale production technology using only labor (L_X), while a dirty good is produced with a constant returns to scale production technology using labor (L_Y) and emissions (D):

$$X = L_X \tag{1.1}$$

and
$$Y = F(L_Y,\ D) \tag{1.2}$$

For convenience, a unit of X is defined as the amount that can be produced using one unit of labor. The numeraire is labor (or equivalently, X).

The agricultural sector produces a non-taxable clean good (Z) with constant returns to scale technology using only labor as an input:

$$Z = L_Z, \tag{1.3}$$

where a unit of Z is defined as the amount that can be produced using one unit of labor.

Both manufacturing outputs are assumed to be taxable. For environmental reasons, the output of the polluting sector (Y) might be taxed at a rate higher than that of the non-polluting sector (X). This chapter will focus on the differential, that is, the

[11] The governments in many developing countries often have difficulties in finding suitable tax tools, especially when the transaction arises within the household or between households using informal markets. In this sense, a non-taxable clean agricultural good (*Z*) might be interpreted instead as all informal economic activities. See Schneider and Enste (2000) for an empirical assessment of the size of the underground economy for developing countries as well as OECD countries.

[12] It is well known that many countries exempt consumption taxes on foods and other agricultural products for the purpose of income distribution.

extra tax on the output of the dirty industry. In addition, note that any uniform tax on outputs X and Y is equivalent to a tax on labor used in those two sectors, since labor is the only source of income in this model. For these reasons, this model will use a tax on labor (t_L) to represent the uniform or common portion of the output taxes on X and Y. Then, the output tax on a dirty consumption good (t_Y) is the extra tax on output of the dirty industry.

Emissions (D) are a dirty input that can be disposal of gaseous, liquid, and solid waste used to produce output. Note that the production function for Y has variable pollution, D per unit of output. This disposal is assumed to inflict some *private* cost on producers in terms of resources (labor), and a unit of emissions can be defined as the amount that requires one unit of resources:

$$D = L_D . \tag{1.4}$$

Thus, the firm has constant private marginal cost of pollution, equal to one, so it chooses a finite amount of pollution. Because of the negative externality, however, the firm's choice is not socially optimal. Aggregate emissions (ND) have a harmful effect on overall environmental quality (E):

$$E = e(ND), \tag{1.5}$$

where $e' \equiv \partial e / \partial D < 0$. The model also assumes perfect competition, certainty, complete information, and perfect factor mobility between sectors.

Government produces a public good using labor:

$$G = NL_G . \tag{1.6}$$

Government finances the public good with the tax on market labor (t_L) and the output tax on a dirty consumption good (t_Y), and possibly a tax on emissions (t_D). Hence, the government budget constraint is

$$G = N\left(t_L L + t_Y Y + t_D D\right). \tag{1.7}$$

For convenience, the consumer price for the polluting manufactured good (c_Y) is defined as the sum of the producer price (p_Y) and the output tax (t_Y). The nominal wage is normalized to one, and $p_X = p_Z = 1$ as well. Without loss of generality, assume that the initial producer price of Y is normalized to one (i.e., $p_Y = 1$).

Finally, the economy's overall resource constraint is given by

$$NL = NX + N\left(L_Y + D\right) + G. \tag{1.8}$$

A representative household maximizes the utility function, $U = U(X,\ Y,\ Z;\ G,\ E)$, subject to the budget constraint, $(1 - t_L)L = X + (1 + t_Y)Y$. Taxable labor supply is given by $L = L_X + L_Y + L_D + L_G$. From the first-order conditions, we have $U_X = U_Y/(1 + t_Y) = U_Z/(1 - t_L) = \lambda$, where a subscript on U denotes a marginal utility from that good (U_Z is the partial derivative of U with respect to L_Z), and λ is the private marginal utility of income.[13]

Using log-linearization techniques, appropriate for small changes, I derive equations that show the impacts of a tax change on prices, quantities, and welfare.

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[13] In the representative household's utility maximization, it is assumed that she considers the environmental quality (E) and the public good (G) to be independent of her own choices. This assumption is appropriate if the number of consumers (N) is large.

In general, I start at an initial competitive equilibrium with possible pre-existing t_L, t_Y, and t_D. Special cases are considered where one or more of those taxes are not possible (i.e., are set to zero). The model then can be used to show all of the effects of a small increase in the emissions tax or if that is not possible, then a small increase in the output tax. In all cases, the revenue is returned through a reduction in the pre-existing tax on market labor so that G is not affected $(dG = 0)$. The effect of any such change on utility can be expressed by totally differentiating the household's utility function:

$$dU = U_X dX + U_Y dY - U_Z dL + U_E N e' dD. \tag{1.9}$$

Totally differentiate the overall resource constraint (1.8), divide it by N, and set $dG = 0$, to get:

$$dX = dL - dL_Y - dD. \tag{1.10}$$

Next, plug the first-order conditions from the utility maximization and (1.10) into (1.9), and divide it by the Lagrange multiplier (λ), to get:

$$dU/\lambda = dX + (1 + t_Y) dY - (1 - t_L) dL - \mu dD, \tag{1.11}$$

where dU is the change in a representative household's utility. The term μ equals $-NU_E e'/\lambda$ and denotes the MED from emissions.

Totally differentiate the production function of the dirty good (1.2):

$$dY = F_{L_Y} dL_Y + F_D dD, \tag{1.12}$$

where $F_i \equiv \partial F(\bullet)/\partial i$ for $i = L_Y$ and D. Then, substitute the first-order conditions from the profit maximization into (1.12) to get:[14]

$$dY = dL_Y + (1 + t_D)\, dD. \tag{1.13}$$

Finally, plug (1.13) into (1.11) and divide the both sides of the equation by L, then

$$\frac{dU}{\lambda L} = t_L \hat{L} + t_Y \left(\frac{Y}{L}\right)\hat{Y} + (t_D - \mu)\left(\frac{D}{L}\right)\hat{D}, \tag{1.14}$$

where a hat over a variable denotes a percentage change (e.g., $\hat{L} = dL/L$). The left hand side of this expression is the change in welfare in terms of a particular monetary unit (dU/λ) as a fraction of the total return to market labor in the economy (L). The right hand side consists of three parts. The first and second parts are the welfare effects of the environmental policy through its impact on the amount of the market labor $(\hat{L})$ and the dirty manufactured good $(\hat{Y})$. The third term is the welfare impact resulting from the change in pollution $(\hat{D})$. Note that if either a tax on the market labor (t_L) or the extra consumption tax on the dirty good (t_Y) is set to zero, then the corresponding welfare effect disappears from the equation. Also note that, even without any pre-existing taxes $(t_L = t_Y = 0)$ in theory, the developing country can successfully internalize the externality by imposing a Pigouvian tax on emissions (t_D) equal to the MED (μ). The rate $t_D = \mu$ then maximizes utility $(dU = 0)$.

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[14] Maximizing the profit function, $\Pi = F(L_Y,\, D) - L_Y - (1 + t_D)D$, gives the first-order conditions: $F_{L_Y} = 1$ and $F_D = (1 + t_D)$.

Next, totally differentiate the government budget constraint (1.7), divide it by the total amount of labor supply in the manufacturing sectors (NL), hold G fixed $(dG = 0)$, and divide it again by $(1 - t_L)$ to get:

$$\hat{t}_L = -\frac{t_L}{(1-t_L)}\hat{L} - \frac{(1+t_Y)Y}{(1-t_L)L}\left[\hat{t}_Y + \frac{t_Y}{(1+t_Y)}\hat{Y}\right] - \frac{(1+t_D)D}{(1-t_L)L}\left[\hat{t}_D + \frac{t_D}{(1+t_D)}\hat{D}\right], \quad (1.15)$$

where $\hat{t}_L \equiv dt_L/(1-t_L)$, $\hat{t}_D \equiv dt_D/(1+t_D)$, and $\hat{t}_Y \equiv dt_Y/(1+t_Y)$. This is the change in t_L necessary for government to balance the budget when changing t_Y or t_D. To evaluate this expression, the next step is to solve for $\hat{L}$, $\hat{Y}$, and $\hat{D}$ in terms of two environmental tax instruments: $\hat{t}_Y$ and $\hat{t}_D$.

In order to find analytical solutions to (1.14) and (1.15), one needs to make some assumptions on consumer preferences. In particular, assume that environmental quality (E) and the public good (G) are separable from the consumption goods $(X,\ Y, \text{ and } Z)$ and that the consumption goods enter utility in a homothetic sub-utility function as in Bovenberg and de Mooij (1994) or Fullerton and Metcalf (2001):

$$U(X,\ Y,\ Z;\ G,\ E) = U\big(V\big(Q(X,\ Y),\ Z\big),\ G,\ E\big), \quad (1.16)$$

where $V(\bullet)$ and $Q(\bullet)$ are both homothetic. For later use, define p_Q as a price index on $Q(X,\ Y)$ such that

$$p_Q Q = p_X X + c_Y Y \quad (1.17)$$

and let w be the real net wage, $w = (1-t_L)/p_Q$.

Totally differentiate (1.17) and divide it by p_Q to get:

$$\hat{p}_Q = \frac{Y}{(1-t_L)L}\hat{p}_Y + \frac{(1+t_Y)Y}{(1-t_L)L}\hat{t}_Y. \tag{1.18}$$

Since $p_X = 1$ always, the change in the overall price index $(\hat{p}_Q)$ depends on the change in the producer price of a dirty good $(\hat{p}_Y)$ and the change in its output tax $(\hat{t}_Y)$.

For the change in the producer price of a dirty output $(\hat{p}_Y)$, Appendix A.1 shows how to use the zero-profit condition and the first-order conditions from profit maximization to obtain:

$$\hat{p}_Y = \frac{(1+t_D)D}{Y}\hat{t}_D. \tag{1.19}$$

Substitute (1.19) into (1.18) to get:

$$\hat{p}_Q = \frac{(1+t_Y)Y}{(1-t_L)L}\hat{t}_Y + \frac{(1+t_D)D}{(1-t_L)L}\hat{t}_D. \tag{1.20}$$

This equation says that an increase in either t_Y or t_D results in an increase in the overall price index, and that the contribution of each depends on the expenditure shares of Y and D in after-tax labor income from the manufacturing sectors.

The definition of the real wage rate implies that $\hat{w} = -\hat{t}_L - \hat{p}_Q$. Thus:

$$\hat{w} = -\hat{t}_L - \frac{(1+t_Y)Y}{(1-t_L)L}\hat{t}_Y - \frac{(1+t_D)D}{(1-t_L)L}\hat{t}_D. \tag{1.21}$$

This equation says that the real net wage decreases if any tax were to increase. Again, the contribution to the change in the real net wage depends on each expenditure share. Substitute (1.15) into (1.21) to get:

$$\hat{w} = \frac{t_L}{\left(1 - t_L\right)}\hat{L} + \frac{t_Y Y}{\left(1 - t_L\right)L}\hat{Y} + \frac{t_D D}{\left(1 - t_L\right)L}\hat{D}\,. \tag{1.22}$$

Subsistence agriculture $\left(Z\right)$ is non-taxable and therefore operates in this model much like home production such as work in the household cooking, cleaning, child care, and gardening to grow food for the family. Therefore, the choice between market labor and home/agricultural labor acts in this model much like a labor-leisure choice in other models such as Bovenberg and de Mooij (1994) and Fullerton and Metcalf (2001). Thus, the next step is the derivation of a "labor supply" function, meaning the supply of labor to the market manufacturing sectors rather than to the non-market home/agricultural sector.

Maximization of the household's sub-utility for the composite manufactured good $\left(Q\right)$ and a clean agricultural good $\left(V\left(Q,\ Z\right)\right)$ subject to the budget constraint $\left(Q = wL\right)$ gives the function for the supply of labor to the manufacturing sectors, $L = L(w)$, and totally differentiating it yields:

$$\hat{L} = \varepsilon \hat{w}\,, \tag{1.23}$$

where ε is the uncompensated elasticity of this labor supply in the manufacturing sectors with respect to the net wage (i.e., $\varepsilon \equiv w\partial L \big/ L\partial w$).

The equations above can be used to solve for any change as a function of the exogenous tax change, exogenous parameters, and initial values of the variables.

Appendix B shows how these equations are used to solve for the key variables ($\hat{D}$, $\hat{Y}$, and $\hat{L}$).

First, the change in emissions can be expressed as follows:

$$\hat{D} = -\Theta \left\{ \begin{array}{c} \sigma_Q (1-\phi)[1-(1+\varepsilon)t_L]\hat{t}_Y \\ \\ +\left[\sigma_Q (1-\phi)[1-(1+\varepsilon)t_L]\dfrac{(1+t_D)D}{(1+t_Y)Y} + \sigma_Y \left(\dfrac{L_Y}{Y}\right)\left[1-(1+\varepsilon)\left(t_L + t_Y \dfrac{Y}{L}\right)\right]\right]\hat{t}_D \end{array} \right\},$$

(1.24)

where $\phi \equiv (1+t_Y)Y/(1-t_L)L$ and
$\Theta \equiv \left\{1-(1+\varepsilon)\left[t_L + t_Y\left(Y/L\right) + t_D\left(D/L\right)\right]\right\}^{-1}$.[15]

Note that the σ_Q part of $\hat{t}_D$ term is similar to the $\hat{t}_Y$ term. They represent the substitution in consumption. The σ_Y part of $\hat{t}_D$ term represents the substitution in inputs for production.

For $\hat{Y}$:

$$\hat{Y} = -\Theta \left\{ \begin{array}{c} \sigma_Q (1-\phi)[1-(1+\varepsilon)t_L]\hat{t}_Y \\ \\ +\left[\sigma_Q (1-\phi)[1-(1+\varepsilon)t_L]\dfrac{(1+t_D)D}{(1+t_Y)Y} + \sigma_Y \left(\dfrac{L_Y}{Y}\right)(1+\varepsilon)t_D\left(\dfrac{D}{L}\right)\right]\hat{t}_D \end{array} \right\}. \quad (1.25)$$

Since both $\hat{D}$ and $\hat{Y}$ are used in the key welfare equation (1.14), these two equations ((1.24) and (1.25)) deserve further discussion. First, note that both equations have the same term for an incremental tax change of the output tax (i.e., the $\hat{t}_Y$ term). It shows that if the developing country government increases (or introduces) t_Y marginally and holds the level of the Pigouvian tax fixed (i.e., $\hat{t}_D = 0$), the effects on both the dirty input (D) and a dirty output (Y) are the same in magnitude (i.e., $\hat{Y} = \hat{D}$). Holding $\hat{t}_D = 0$ means that the government cannot (or need not) use the Pigouvian tax as an instrument for environmental improvement. This result just reflects the fact that the output tax change $(\hat{t}_Y)$ will reduce output. No change in relative input prices $(\hat{t}_D = 0)$ means that both inputs will be reduced in the same proportion ($\hat{Y} = \hat{D} = \hat{L}_Y$).

Next consider the second terms in (1.24) and (1.25) that are multiplied by $\hat{t}_D$. This *change* in relative input prices can affect D differently than Y, but only when σ_Y is not zero. With substitution in production, the firm can reduce pollution more than output $(\hat{D} \neq \hat{Y})$ and change pollution per unit of output, by an extent that increases with σ_Y. To clarify, note that if $\sigma_Y = 0$ in (1.24) and (1.25), then $\hat{t}_D$ has the exact same effect on $\hat{D}$ as an $\hat{Y}$. This corresponds to the special case where the dirty good itself generates externalities either in production or in consumption. Equivalently, suppose that pollution per unit of output is fixed. Then, the tax on a dirty output has the same effect on that output as it has on the dirty input. For example, final consumption goods such as gasoline and cigarettes may have

[15] One important assumption is that $\Theta > 0$. Since $G/NL = t_L + t_Y(Y/L) + t_D(D/L)$ from the government's budget constraint, this assumption means that the following condition needs to be satisfied: $\varepsilon < (NL - G)/G$.

environmental problems that come not from one of the inputs to production, but from the use of the final consumption good, so the pollution per unit of output is fixed. Therefore, $\hat{Y} = \hat{D}$, so the government can achieve the same amount of reduction in pollution either by imposing an output tax or tax on pollution. In general, however, this model *does* allow for substitution $(\sigma_Y \neq 0)$.

Finally, for $\hat{L}$:

$$\hat{L} = -\Theta\varepsilon \left\{ \begin{array}{c} \sigma_Q (1-\phi)\left[t_Y\left(\dfrac{Y}{L}\right) + t_D\left(\dfrac{D}{L}\right)\right]\hat{t}_Y \\ \\ +\left[\sigma_Q (1-\phi)\left[t_Y\left(\dfrac{Y}{L}\right) + t_D\left(\dfrac{D}{L}\right)\right]\dfrac{(1+t_D)D}{(1+t_Y)Y} + \sigma_Y\left(\dfrac{L_Y}{Y}\right)t_D\left(\dfrac{D}{L}\right)\right]\hat{t}_D \end{array} \right\}. \quad (1.26)$$

Since $\Theta > 0$, $\varepsilon > 0$, and all of the terms inside the large brackets are positive, an increase in either t_Y or t_D *does* reduce labor use in the manufacturing sectors. This equation completes the solution for the necessary variables ($\hat{D}$, $\hat{Y}$, and $\hat{L}$) to enter the key equation (1.14) for the change in welfare of the economy.

If non-taxable production is clean as assumed, then environmental tax policy could generate further reductions in pollution levels through the indirect channel of reduced labor supply to taxable sectors. If instead subsistence agriculture is polluting, then environmental policy using tax instruments could cause an unwanted *increase* in the overall level of pollution. Moreover, the environmental problem could become worse, since pollution generated in the non-taxable sector cannot be regulated at all. This kind of dilemma arises when controlling inputs rather than emissions: if all inputs cannot be regulated, partial application of sub-optimal input taxes might result in unwanted substitutions among inputs and therefore might aggravate the problem.

However, it is unclear whether the sector Z is environmentally benign. In many developing countries, agricultural (or traditional) sectors have both characteristics: on the one hand, they usually employ environmentally-benign production technology such as less use of chemical fertilizer and tilling the soil with animals. In that case, environmental tax policy could achieve further reduction in the overall pollution level in the society by shifting labor to non-market activity. On the other hand, some developing countries like Brazil have been trying hard to reduce harmful farming activities such as slash-and-burn farming. In that case, the effect could be the opposite.[16]

1.5 TAX REFORM AND OPTIMAL TAX RATES

1.5.1 Tax Reform

Suppose that the government of a developing country is considering a tax reform by raising (or introducing) t_Y with pre-existing labor tax, holding t_D fixed (i.e., $t_L > 0$, $t_D \geq 0$, $t_Y \geq 0$ and $\hat{t}_Y > 0$ but $\hat{t}_D = 0$). Then, substituting (1.24), (1.25), and (1.26) into (1.14):

$$\frac{dU}{\lambda L} = -\Theta\left[\sigma_Q(1-\phi)(1-t_L)\mathrm{A}\right]\hat{t}_Y, \tag{1.27}$$

where $\mathrm{A} \equiv t_Y\left(Y/L\right) + t_D\left(D/L\right) - \left\{1-\varepsilon\left[t_L/(1-t_L)\right]\right\}\mu\left(D/L\right)$.

[16] Eskeland and Jimenez (1992) point out that small firms in the informal sector are often major polluters in developing countries. If I interpret Z as the informal sector rather than as subsistence farming, then that increases the probability of an unwanted increase in the overall pollution level.

Note that this incremental tax reform has no substitution effect between inputs. Though σ_Y is still nonzero, it is not relevant for $\hat{t}_Y$. By imposing this additional output tax, the government can reduce the consumption level of a dirty good, but it cannot induce the producers to substitute other cleaner inputs for emissions in production. Therefore, the change in t_Y has no substitution effect in production (i.e., σ_Y does not appear in (1.27)). Also note how the formula simplifies with no pre-existing taxes:

$$\frac{dU}{\lambda L} = \sigma_Q\left(1-\frac{Y}{L}\right)\mu\left(\frac{D}{L}\right)\hat{t}_Y\,, \tag{1.27a}$$

Welfare is always increased by a small increase in the output tax from zero if $\sigma_Q > 0$. However, as will be shown later, the magnitude of the net welfare effect from the output tax is smaller than that of the Pigouvian tax, due to the lack of a substitution effect.

Next, suppose the government raises (or introduces) t_D with the pre-existing labor tax, holding t_Y fixed (i.e., $t_L > 0$, $t_Y \geq 0$, $t_D \geq 0$, and $\hat{t}_D > 0$ but $\hat{t}_Y = 0$). Then, the welfare expression (1.14) simplifies:

$$\frac{dU}{\lambda L} = -\Theta\left\{\sigma_Q(1-\phi)(1-t_L)\left[\frac{(1+t_D)D}{(1+t_Y)Y}\right]\mathrm{A} + \sigma_Y\left(\frac{L_Y}{Y}\right)\mathrm{B}\right\}\hat{t}_D\,, \tag{1.28}$$

where $\mathrm{B} \equiv t_Y\left(Y/L\right)\mu\left(D/L\right) + (1-t_L)\left\{t_D\left(D/L\right) - \left[1-\varepsilon\left(t_L/(1-t_L)\right)\right]\mu\left(D/L\right)\right\}$.

The first term in the large brackets represents the output effect as before (i.e., the substitution in consumption from σ_Q). The second term is the substitution effect in production from σ_Y: the producers can substitute one input for another as the relative input prices change due to $\hat{t}_D$. In other words, a small increase in the t_D raises the consumer price for Y and the consumers moves away from Y to X (and possibly to Z) due to higher price. As a result, the environmental quality improves and the welfare rises.

However, the output effect from t_D is smaller than the same effect from t_Y. Though similar to equation (1.27) in appearance, the first term in the large brackets (i.e., the σ_Q term) of equation (1.28) has an additional multiplicative term, $(1+t_D)D/(1+t_Y)Y$ in it. This is the ratio of expenditure on the dirty input to the revenue from selling the output, and it is always less than one. Thus, the output effect from t_D is always smaller than the same effect from t_Y.

The real strength of t_D, however, comes not from the output effect, but from the substitution effect. Unlike $\hat{t}_Y$ back in equation (1.27), the Pigouvian tax in (1.28) penalizes the use of D and induces the producers of Y to shift into more use of L_Y. This ability to abate emissions by input substitution is a very powerful way to improve the environment, and it thus increases the overall social welfare. As I will show later in the numerical simulation, the size of σ_Y is very important to decide the size of welfare gain. However, many developing countries appear to have much lower σ_Y than in developed countries. For example, global coal use over the next two decades is expected to rise more than 50 percent, mostly in the developing world and especially in Asia. In particular, industry accounts for two thirds of China's coal use. Industrial boilers alone consume 30 percent of China's coal. Despite the government's large investments, these highly inefficient boilers are still widely used (WRI, 1998). Hence, developing countries have difficulties in switching to more efficient and less polluting production technologies.

1.5.2 Optimal Tax Rates

Now I explicitly solve for the optimal tax rates for both t_Y and t_D and briefly discuss their implications.

First, the second-best optimal tax on emissions (t_D^*) with pre-existing t_L can be obtained from (1.28) by setting $dU = 0$ and $t_Y = 0$:

$$t_D^* = \mu\left[1 - \varepsilon\left(\frac{t_L}{1 - t_L}\right)\right]. \tag{1.29}$$

Note that $t_D^* < \mu$ since $\left[1 - \varepsilon\left(t_L/(1 - t_L)\right)\right] < 1$, unless $t_L = 0$ or $\varepsilon = 0$, which is consistent with Bovenberg and de Mooij (1994). As Fullerton, et al (2001) point out, equation (1.29) can be rewritten as follows:

$$t_D^* = \frac{\mu}{\Psi}, \tag{1.29a}$$

where Goulder and Williams (1999) show that the partial equilibrium marginal cost of public funds Ψ is $\left[1 - \varepsilon\left(t_L/(1 - t_L)\right)\right]^{-1}$.

With pre-existing t_L and t_Y, the second-best optimal tax rate on emissions $\left(t_D^{**}\right)$ looks much more complicated. Before solving it explicitly, it can be shown that the second-best optimal tax rate on emissions still is less than the marginal environmental damages. Define $\theta \equiv \left(1 + t_D^{**}\right)\left(D/Y\right)$, which is the pollution intensity of Y at t_D^{**} from (1.29a).[17] Rewrite equation (1.28) with $dU = 0$ to make a basic point:

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[17] Since $Y = F\left(L_Y, D\right)$, the remaining share of output is $\left(1 - \theta\right) \equiv L_Y/Y$.

$$\left(t_D^{**}-\mu\right)=-\left\{\frac{\begin{array}{c}\theta\sigma_Q(1-\phi)\left(\dfrac{Y}{D}\right)\left[(1-t_L)t_Y+\varepsilon t_L\mu\left(\dfrac{D}{Y}\right)\right]\\+(1-\theta)\sigma_Y(1+t_Y)\mu\left[(1+\varepsilon)t_Y\left(\dfrac{Y}{L}\right)+\varepsilon t_L\right]\end{array}}{(1-t_L)\left[\theta\sigma_Q(1-\phi)+(1-\theta)\sigma_Y(1+t_Y)\right]}\right\}. \tag{1.30}$$

Since the right-hand side of equation (1.30) is always negative, the second-best optimal Pigouvian tax with pre-existing t_L and t_Y is less than the social marginal environmental damages (μ).

The explicit analytical solution for t_D^{**} is much more complicated, because the t_D^{**} term appears in the both sides of equation (1.30). However, a positive and real value of the root of the second-best optimal Pigouvian tax $\left(t_D^{**}\right)$ can be obtained as follows:

$$t_D^{**}=\frac{-\left(\alpha\sigma_Q+\beta\sigma_Y\right)+\sqrt{\left(\alpha\sigma_Q+\beta\sigma_Y\right)^2-4\gamma\sigma_Q\left(\delta\sigma_Q+\kappa\sigma_Y\right)}}{2\gamma\sigma_Q}, \tag{1.31}$$

where $\alpha\equiv(1-\phi)\left(D/Y\right)\left[(1-t_L)\left(D/L\right)+(1-t_L)t_Y\left(Y/L\right)-(1-t_L-\varepsilon t_L)\mu\left(D/L\right)\right]$,
$\beta\equiv(1-t_L)\left(D/L\right)(1+t_Y)\left(L_Y/Y\right)$, $\gamma\equiv(1-\phi)\left(D/Y\right)(1-t_L)\left(D/L\right)$,
$\delta\equiv(1-\phi)\left(D/Y\right)\left[(1-t_L)t_Y\left(Y/L\right)-(1-t_L-\varepsilon t_L)\mu\left(D/L\right)\right]$, and
$\kappa\equiv(1+t_Y)\left(L_Y/Y\right)\mu\left(D/L\right)\left[(1+\varepsilon)t_Y\left(Y/L\right)-(1-t_L-\varepsilon t_L)\right]$ for
$\left(\alpha\sigma_Q+\beta\sigma_Y\right)^2\geq 4\gamma\sigma_Q\left(\delta\sigma_Q+\kappa\sigma_Y\right)$.

Note the difference between the second-best optimal Pigouvian tax $\left(t_D^{*}\right)$ with pre-existing labor tax from (1.29) and the second-best one with pre-existing labor and emissions taxes $\left(t_D^{**}\right)$ from (1.31). The t_D^* only depends on the pre-existing t_L, ε, and μ. However, t_D^{**} becomes much more difficult to calculate. It is required for the environmental authority to have information on technological and structural parameters. In developing countries, however, many administrative problems such as poor record keeping, unreliable and insufficient data, and shortage of trained officials are widespread. Thus, this heavy requirement for additional information would make it more difficult to implement emissions tax in developing countries.

The second-best optimal tax on output $\left(t_Y^{**}\right)$ with the pre-existing t_L and t_D, however, looks simpler. It can be obtained by setting the numerator of equation (1.28) to zero:

$$t_Y^{**} = \left[1 - \varepsilon\left(\frac{t_L}{1 - t_L}\right)\right](\mu - t_D)\left(\frac{D}{Y}\right). \tag{1.32}$$

Again, using the definition of the partial equilibrium marginal cost of public funds (Ψ), the equation (1.32) can then be rewritten:

$$t_Y^{**} = \left(\frac{\mu}{\Psi}\right)\left(\frac{D}{Y}\right) - t_D\left(\frac{D}{Y}\right). \tag{1.32a}$$

Note that if $t_D = 0$, then equation (1.32a) collapses and $t_Y^{**} = t_Y^*$ in the form:

$$t_Y^{**} = t_Y^* = \left(\frac{\mu}{\Psi}\right)\left(\frac{D}{Y}\right) = t_D^*\left(\frac{D}{Y}\right), \tag{1.32b}$$

which is the output effect from the second-best output tax. If t_Y is employed, the economy has two different sources of distortions: first, the output tax increases the consumer price (c_Y) so that demand for Y decreases (if $\sigma_Q > 0$). Second, the output tax raises the overall consumer price $\left(p_Q\right)$ so that the household reduces its demand for the composite consumption good (Q) and, if $\varepsilon > 0$, increases the non-taxable agricultural good (Z). Since t_D has an output effect as well as the substitution effect, the second term in (1.32a) means that the tax rate t_Y needs to be adjusted for the output effect already obtained from taxing emissions. Note that $t_Y^{**} = 0$, if $t_D = \mu/\Psi$. In other words, if emissions are taxed optimally, then the tax rate on output should be zero.[18]

Also note that if the optimal emissions tax t_D^* is unavailable, and $t_D = 0$, then equation (1.32b) says that the second-best optimal t_Y is the desired emissions tax $\left(t_D^*\right)$ times emissions per unit of output $\left(D/Y\right)$. In other words, the second-best optimal t_Y is equal to the social marginal environmental damage per unit of output. Fullerton, et al (2001) discuss the implication of the similarity between t_Y^* and t_D^*: if the ideal emissions tax is unavailable, then the output tax should be set to generate exactly the same output effect as the ideal emissions tax.

An important policy implication of this result is that even if the authorities cannot tax emissions due to the difficulties of monitoring and enforcement or other administrative constraints, it does not mean that they have to over-tax the output. This point may be particularly relevant to many developing countries, since their monitoring and enforcement capabilities are less than in developed countries. They just need to

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[18] If t_D is set sub-optimally and fixed, while t_Y can vary, then t_Y should be raised by the additional desired output effect to cover for the under-taxation of emissions.

know the ratio of the dirty input to the output $\left(D/Y\right)$, which can be obtained by estimating the general input structures of polluting firms. Furthermore, if firms are similar to each other in terms of their production technology, it would be much easier for the environmental authorities to obtain this ratio without much burden. Many developing countries have manufacturing sectors that consist of relatively less diverse industries than in developed countries. Factories in the same industry also usually share relatively homogeneous and simple production technology. If so, the effort to improve environmental quality in developing countries becomes less burdensome.

1.6 NUMERICAL SIMULATION

In this section, equations (1.27) and (1.28) are used to measure the impact on welfare of a small change in either t_D or t_Y. This section employs parameter values from China, which in many respects has structural characteristics commonly found in many developing countries: a large agricultural sector, heavy dependence on indirect consumption taxes, widespread use of polluting inputs and out-dated technologies, and many geographically dispersed small point-source polluters such as Town and Village Enterprises. In the next subsection, various parameters are selected.

It is important to remember that I use the parameter values from China as an example of developing countries. I do not claim that China be considered a *prima facie* representative developing country in every possible respect. No single country can be considered to have all the institutional and structural characteristics in many developing countries over the world. I only say that China has some institutional and structural characteristics relevant to the hypothesis presented in this chapter. The same reservation is explicitly made for for the U.S. used here as an example of developed countries.

1.6.1 Assumptions on Parameters

To measure the impact on welfare of an incremental change in either t_Y or t_D, equations (1.27) and (1.28) require values for many elasticities, shares, and initial tax rates.

For t_L, I want a tax rate that applies to the income from all household resources supplied to the market. Although the top marginal personal income tax rate in China is 45 percent, the average taxpayer faces only a 15 percent marginal tax rate (Heritage Foundation, 2000).[19] However, indirect consumption taxes such as the VAT, consumption tax, and excise taxes are usually applied to both clean and dirty manufacturing sectors in addition to the direct personal and enterprise income taxes. Currently, the VAT rate of 17 percent is applied to a large proportion of domestically-produced goods and services as well as to imported goods. However, the VAT is levied at a lower rate of 13 percent for the basic foodstuffs and agricultural goods.[20] Assuming that the VAT rate for foods and agricultural goods is the basic rate applied to every household regardless of economic activity, I safely choose 10 percent for the additional portion of tax burden from various indirect taxes. Therefore, the final rate for t_L is 0.25.

For t_Y, I need additional tax rate that applies only to the income from all market household resources engaged in polluting production activities (Y). As mentioned above, the VAT is applied differently: the 17 percent rate applies to

[19] This number can be justified by another calculation. China's GDP per capita was US $3,600 in 1998, which was about 30,000 yuan (IMF, 1999a and 1999b). Applying a standard deduction of 800 yuan per month, taxable income amounts to 24,000 yuan. The tax rate for this income category is currently 15 percent (Tseng, et al, 1994).

[20] It is reduced further for goods and services provided by small-scale taxpayers (6 percent). Furthermore, the business tax is applied at 3 to 5 percent to all enterprises, institutions, or individuals providing certain types of services, assign intangible assets, or sell immovable property within China, if their turnover is greater than a threshold specified by the Ministry of Finance (Tseng, et al, 1994).

produced goods in Y, the 13 percent rate applies to in X, and untaxed subsistence agriculture is part of Z. Therefore, the difference between Y and X is 4 percent. However, I will safely assume 5 percent for t_Y, because some excise taxes are levied at 3 to 8 percent on some goods such as motor vehicles (Ma, 2000).

For the uncompensated wage elasticity of market labor supply (ε), I need a single value to represent an aggregate of all workers in the manufacturing sectors and all market labor supply effects from changes in wages of the manufacturing sectors. In the case of developed countries, the literature provides many estimates of the hours elasticity that are small (or negative) for males, and other estimates that are large and positive for females. Although no specific estimates of uncompensated wage elasticities are available for China, numerous studies such as Rosenzweig (1980) and Jacoby (1993) show that the magnitudes are not much different from those in developed countries. In this model, however, ε represents elasticity of supply to the market sector rather than the non-market sector. So, I believe $\varepsilon = 0.3$ reasonable value. I also vary these numbers for sensitivity analysis later.

For Y/L, I calculate the proportion of the industries most responsible for pollution in total production. As of 1998 in China, almost 1.8 million collectively-owned enterprises currently operate and often use obsolete production technologies and pollute more than other types of firms (World Bank, 1997). The 1998 data from National Bureau of Statistics (1999) shows that the polluting industries constitute slightly more than 50 percent of GDP, so I use 0.50 for Y/L.[21] Since the magnitude of ϕ depends on the pre-existing t_L and t_Y as well as Y/L, for

[21] See Appendix A.3 for the list of polluting industries.

example, the choices for those parameters imply that $\phi = 0.70$ for $t_L = 0.25$ and $t_Y = 0.05$.[22] In other words, these polluting goods are primarily manufacturing goods, so 50 percent of total output represents almost 70 percent of private consumption of polluting manufactured goods.

For D/Y, I want an aggregate share for pollution in the dirty output. In China, many households as well as private firms still use energy-inefficient coal-burning boilers for heating. And the proportion of coal in total energy supply is estimated to drop less than 10 percentage point for the next 20 years (US DOE, 1999). Based on this evidence and the "final use" part of the 1997 input-output table from National Bureau of Statistics (1999), I calculate that the ratio of polluting inputs in total polluting output is about 55 percent. So, I use $D/Y = 0.50$ without giving false sense of precision.

Estimates for the elasticities of substitution in consumption (σ_Q) and production (σ_Y) are not available for the specific aggregation in this model. For the case of developed countries, such as the U.S., Fullerton and Metcalf (2001) and Fullerton, et al (2001) assume that both elasticities are close to one, as is broadly consistent with the empirical literature on substitution in consumption and production. However, it might be too far-fetched to assume that the situation would be the same in developing countries: much anecdotal evidence indicates that those substitution elasticities may be much lower than in developed countries. Hence, considering these factors, the baseline simulation for China is assumed here to employ 0.50 for both σ_Q and σ_Y. I also vary these numbers for sensitivity analysis later.

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[22] Recall that ϕ is defined as $(1+t_Y)Y/(1-t_L)L$.

Finally, the model requires a measure of MED (μ). Jha and Whalley (2001) review some estimates of environmental costs in selected Asian countries. In particular, they report that China has estimated environmental costs that are 5.5 to 9.8 percent of GDP (where measured GDP includes X and Y but not Z). Unfortunately, this estimate is average damage rather than marginal damage. Moreover, their number is a more comprehensive measure than those from developed countries.[23] Hence, for the case of developing countries, I use 5 percent of GDP for the estimate of damages. Then, since Y is assumed 50 percent of GDP, damages are about 10 percent of Y. Moreover, since $D/Y = 0.50$, damages would be about 0.2 per unit of D ($\mu = 0.20$).

Table 1.1 summarizes the assumed parameter values for numerical simulation. The first column shows the parameter values for developing countries. The second column shows a different set of parameter values. This case represents more or less the case for developed countries: social marginal environmental damages are lower $(\mu = 0.1)$, both substitution elasticities in consumption and production are higher $(\sigma_Q = \sigma_Y = 1.0)$, marginal labor income tax rate is higher $(t_L = 0.4)$, the ratio of polluting goods to total output is lower $(Y/L = 0.3)$, and the ratio of polluting inputs to polluting output is lower $(D/Y = 0.4)$.[24] I use this alternative set of parameter values to investigate how the size of net welfare gain from using emissions taxes is

[23] Unlike the studies on the environmental damages in developed countries such as Pearce and Turner (1990) on the Netherlands or Freeman (1982) on the U.S., Jha and Whalley (2001) include not only health and productivity losses from pollution in urban areas (1.7-2.5 percent of GDP) but also productivity losses due to soil erosion, deforestation, and land degradation, water shortage and destruction of wetlands (3.8 to 7.3 percent) into the category.

[24] These parameter values for developed countries are similar to those used in Fullerton, et al (2001). The rationale for this alternative set of parameters can be found there.

changed due to various structural constraints. For a measure of welfare, I use $dU/\lambda L$, the monetary value in yuan of the change in utility as a fraction of market income.

Table 1.1: Assumptions on Parameter Values

	Parameters	Developing Country (e.g., China)	Developed Country (e.g., the U.S.)
μ :	Social marginal environmental damage	0.20	0.10
ε :	Uncompensated elasticity of market labor supply	0.30	0.10
σ_Q :	Substitution elasticity between outputs	0.50	1.00
σ_Y :	Substitution elasticity between inputs	0.50	1.00
t_L :	Average marginal market labor income tax rate	0.25	0.40
t_Y :	Average marginal output tax rate	0.05	0.00
t_D :	Average marginal emissions tax rate	0.00	0.00
Y/L :	Ratio of polluting output to market labor	0.50	0.30
D/Y :	Ratio of emissions to polluting output	0.50	0.40

1.6.2 The Simulation Results

Table 1.2 summarizes the simulation results. The first column shows the developing country case (e.g., China). The first-best Pigouvian tax on emissions would be $\mu = 0.2$, but with a pre-existing tax on market labor $(t_L = 0.25)$, the marginal cost of public funds (Ψ) is 1.1111, and the second-best tax on emissions

$\left(t_D^*\right)$, is 18 percent from (29a). Since the pre-existing t_Y is 0.05, the second-best tax on emissions $\left(t_D^{**}\right)$ with pre-existing t_L and t_Y is about 15 percent from (1.31). Furthermore, since $D/Y = 0.5$, equation (32b) says that the second-best tax on output (t_Y^* with $t_D = 0$) is 9 percent. Note that $t_Y^* = t_Y^{**} = 0.09$ because the pre-existing t_D is assumed to be zero.

On the other hand, the second column shows the developed country case (e.g., the U.S.). Since $\mu = 0.1$ for this case, the first-best t_D would be 0.1. The second-best tax on emissions $\left(t_D^*\right)$ is 9.3 percent, since $\Psi = 1.0714$ with a pre-existing $t_L = 0.4$. The second-best tax on output $\left(t_Y^*\right)$ is 3.7 percent.

Table 1.2: Simulation Results (in percent)

	Developing Country (e.g., China)	Developed Country (e.g., the U.S.)
Pre-existing tax rates		
t_L	25	40
t_Y	5	0
t_D	0	0
Second-best optimal tax rates		
If $t_D = 0$, then t_Y^* should be	9.00	3.73
If $t_Y = 0$, then t_D^* should be	18.00	9.33
If $t_Y = 0.05$, then t_D^{**} should be	14.88	-
Effect on emissions (D) from		
$\hat{t}_Y$	-0.15	-0.50
$\hat{t}_D$	-0.33	-0.80
Effect on the polluting good (Y) from		
$\hat{t}_Y$	-0.15	-0.50
$\hat{t}_D$	-0.08	-0.20
Welfare effects of		
$\hat{t}_Y$	0.0033	0.0060
$\hat{t}_D$	0.0143	0.0096

The simulation results confirm the theoretical prediction in that the effects on D and Y from introducing a small t_D are greater than those from t_Y. In particular, a marginal increase in t_D reduces D by 0.33 percent for a developing country, which is more than twice the size of the decrease in D from t_Y. For a developed country, the decrease in D is greater than in a developing country mainly due to the higher substitution elasticities in production as well as in consumption. Especially, emissions (D) decrease by 0.80 percent if a developed country introduces a small t_D.

The effects on the polluting good (Y) from a marginal increase of either t_Y or t_D are different from the effects on D. In particular, introduction of a small t_Y decreases Y by the exactly same magnitudes as it decreases D in both developing and developed countries. However, the strength of t_D in reducing Y is much weaker. In both developing and developed countries, the magnitudes of reduction in Y from t_D amount to only a quarter of the magnitudes of reduction in D. This is because the change in relative input prices affects D differently than Y, when σ_Y is positive. With substitution in production, the firm can reduce D more than Y and change pollution per unit of output, by an extent that increases with σ_Y. Hence, for both developing and developed countries, the relative strength of t_D (compared to t_Y) is smaller for reducing D and Y.

The welfare gain from introducing a small t_D is *always* greater than that from a small increase in t_Y. Recall that the major strength of an emissions tax is that it provides both output and substitution effects, while the output tax only provides an output effect. For the developed country case, the welfare gain from $\hat{t}_D$ is about 50 percent larger than the gain from $\hat{t}_Y$. For the developing country case, however, the relative strength of $\hat{t}_D$ over $\hat{t}_Y$ becomes larger: 0.0143 percent, which is more than *four* times greater than the gain (0.0033 percent) from $\hat{t}_Y$.

Another interesting point is that the welfare gain from $\hat{t}_D$ is larger for a developing country than for a developed country. For example, $\hat{t}_D$ increases welfare by 0.0143 percent for a developing country but it is only 0.0096 percent for a developed country. This result is quite robust for the assumptions on some important parameters, as shown in the sensitivity analyses.

One important policy implication from this result is that the potential welfare loss from not being able to use t_D could be bigger in developing countries. The difference in the welfare gains between $\hat{t}_Y$ and $\hat{t}_D$ is 0.011 percentage points for the developing country case, while it is only 0.0036 percentage points for the developed country case. Administrative difficulties in designing and implementing a perfect emissions tax are by no means easy tasks, even in developed countries. The situations in many developing countries are worse: their institutional weaknesses such as under-funding and inexperience tend even further to limit the effective implementation of emissions taxes. The simulation results imply that the potential welfare loss from using $\hat{t}_Y$ instead of $\hat{t}_D$ might be quite big especially in developing countries.

At this point, it would be interesting to ask how the assumptions on parameters between developed countries and developing countries values affect the simulation results shown above. Table 1.3 shows the decomposition of the simulation results by parameter assumption. The first two columns show the base cases for developed as well as developing countries already shown in Table 1.2. The remaining columns show how the 'developing countries case' results would change as each single parameter value for the developing countries changes to that for the developed countries.

The most striking point of Table 1.3 is that any change in a single parameter value for the case of developing countries can bring not so much reduction in emissions and the polluting good consumption by using either t_Y or t_D. All the numbers in the first four rows show that the reduction rates in D as well as Y from the uses of

t_D and t_Y in the case for developing countries are about a half (and in many cases, one third) of those in the case for developed countries. For example, the change in the substitution elasticity between clean good and polluting good to the level of developed countries $\left(\sigma_Q = 1\right)$ only reduces D by 0.3152 percent using t_Y, which is the largest effect in D for developing countries. This is only 60 percent level of the reduction in D by using t_Y (0.50 percent) for developed countries. These results strengthens the implications drawn from the numerical simulation results in that any tax policies for the purpose of environmental improvement might be limited in their scopes and effects in developing countries without the simultaneous changes in other structural factors..

First, consider the third column that reports how the base simulation results for developing countries change if labor tax rate increases to the level assumed for developed countries $\left(t_L = 0.4\right)$ from that for developing countries $\left(t_L = 0.25\right)$ with other parameter values fixed at the base case for developing countries. With higher labor income tax at 40 percent, the developing country governments still can reduce emissions and the polluting good production by introducing (or raising) either consumption tax or emissions tax. As a result, welfare improves. However, note that the numbers reported in the third column are smaller than those in the second column (the base case for developing countries) in absolute value. It means that higher labor income tax rate makes disposable income smaller and causes larger labor supply distortion, generating less effective results in both reducing emissions and the polluting good consumption and improving welfare.

Table 1.3: The Decomposition of the Simulation Result by Parameter Assumption (in percent)

	Developed Countreis (e.g., the U.S.)	Less Developed Countries (e.g., China)	$t_L = 0.4$	$t_Y = 0.0$	$\mu = 0.1$	$\varepsilon = 0.1$	$\sigma_Y = 1$	$\sigma_Q = 1$	$\frac{Y}{L} = 0.3$	$\frac{D}{Y} = 0.4$
Effect on emissions (D) from										
$\hat{t}_Y$	-0.5000	-0.1576	-0.0670	-0.1667	-0.1576	-0.1559	-0.1576	-0.3152	-0.2986	-0.1576
$\hat{t}_D$	-0.8000	-0.3250	-0.2819	-0.3333	-0.3250	-0.3242	-0.5750	-0.4001	-0.3922	-0.3600
Effect on the polluting Good (Y) from										
$\hat{t}_Y$	-0.5000	-0.1576	-0.0670	-0.1667	-0.1576	-0.1559	-0.1576	-0.3152	-0.2986	-0.1576
$\hat{t}_D$	-0.2000	-0.0750	-0.0319	-0.0833	-0.0750	-0.0742	-0.0750	-0.1501	-0.1422	-0.0600
Welfare effects of										
$\hat{t}_Y$	0.0060	0.0035	0.0013	0.0083	-0.0004	0.0038	0.0035	0.0070	0.0040	0.0019
$\hat{t}_D$	0.0096	0.0143	0.0133	0.0167	0.0061	0.0143	0.0270	0.0160	0.0094	0.0129

The fourth column $(t_Y = 0)$, the case that consumption tax rate is changed to zero, shows that the opposite results happen compared to the case of raising labor income tax rate. With no consumption tax, developing countries can have slightly stronger effects in reducing emissions and the polluting good consumption and in improving welfare by introducing (or raising) either consumption tax or emissions tax. It is because marginal positive change in consumption tax rate considerably decreases the polluting good consumption (-0.1667), which is almost three times bigger than the base case (-0.0670). Therefore, the size of welfare improvement from the use of consumption tax becomes much bigger in this case (0.0083) than the base case (0.0035). It also slightly increases the size of welfare improvement (from 0.0143 to 0.0167) from the introduction of emissions tax.

The fifth column, which is the case that the MEDs become smaller $(\mu = 0.1)$, shows that the effects of t_Y as well as t_D on D and Y do not change from the base case for developing countries. With low level of MEDs and nonzero consumption tax rate (i.e., $\mu = 0.1$ and $t_Y = 0.05$), additional increase of tax rates or introduction of new tax exacerbates the distortions in the economy, whereas the additional effects from environmental improvement from higher tax rates are negligible. Therefore, the welfare effects from the use of t_Y becomes negative (-0.0004). In the case of t_D, welfare increases only marginally (0.0061).

In the case of lower elasticity of market labor supply $(\varepsilon = 0.1)$, which is reported at the sixth column, the effects on pollution reduction and welfare improvement slightly increase compared to the base case for developing countries. This is due to smaller labor distortion generated with environmental taxation.

Both the seventh and eighth columns show how the base case simulation results change if the subsditution elasticity between dirty and clean inputs $(\sigma_Y = 1)$ as well as the one between polluting and clean goods $(\sigma_Q = 1)$ become larger. Note that the higher input substitutability for the polluting good (σ_Y) combined with the use of t_D can greatly reduce emissions (-0.5750), which is twice greater than the reduction rate for base case (-0.3250). On the other hand, the higher consumption goods substitutability (σ_Q) combined with the use of t_Y can greatly reduce D and Y. The changes in welfare follow the same pattern: higher σ_Y with t_D improves welfare twice greater than the base case, while higher σ_Q with t_Y shows twice bigger welfare change than the base case.

The last two (ninth and tenth) columns in Table 1.3 show how the simulation results change when both the ratio of the polluting industries to GDP $(Y/L = 0.3)$ and the ratio of the dirty input to the polluting good production $(D/Y = 0.4)$ become lower. If Y/L becomes lower in developing countries, the change in emissions from the use of t_Y increases. With the consumption substitutability between clean and dirty goods fixed at the base case for developing countries (i.e., $\sigma_Q = 0.5$), smaller portion of dirty good industries in GDP increases the relative strength of tax intruments in reducing pollution. Since t_Y directly affects the consumption of Y by increasing the consumer price of the polluting consumption good, the size of pollution reduction in D and Y becomes most effective when combined with the use of t_Y. The same argument can be applied to the case of lower D/Y and t_D.

1.6.3 Sensitivity Analysis

Some parameter values used in the numerical simulation are uncertain due to measurement problem. Hence, I use some alternative values for the substitution elasticities $\left(\sigma_Q \text{ and } \sigma_Y\right)$ and the elasticity of market labor supply (ε).

Table 1.4: Sensitivity Analyses (in percent)

σ_Q	0.00	0.25	0.50	0.75	1.00	1.50	2.00
Developing Country (e.g. China)							
Welfare gain							
from $\hat{t}_Y$	0.0000	0.0018	0.0035	0.0053	0.0070	0.0105	0.0140
from $\hat{t}_D$	0.0126	0.0135	0.0143	0.0151	0.0160	0.0176	0.0193
Developing Country (e.g. China)							
Welfare gain							
from $\hat{t}_Y$	0.0000	0.0015	0.0030	0.0045	0.0060	0.0090	0.0120
from $\hat{t}_D$	0.0072	0.0078	0.0084	0.0090	0.0096	0.0108	0.0120

σ_Y	0.00	0.25	0.50	0.75	1.00	1.50	2.00
Developing Country							
Welfare gain							
from $\hat{t}_Y$	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
from $\hat{t}_D$	0.0017	0.0080	0.0143	0.0206	0.0270	0.0396	0.0523
Developing Country							
Welfare gain							
from $\hat{t}_Y$	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
from $\hat{t}_D$	0.0024	0.0042	0.0060	0.0078	0.0096	0.0132	0.0168

ε	0.00	0.25	0.50	0.75	1.00	1.50	2.00
Developing Country							
Welfare gain							
from $\hat{t}_Y$	0.0039	0.0036	0.0032	0.0027	0.0021	0.0000	-0.005
from $\hat{t}_D$	0.0143	0.0143	0.0143	0.0142	0.0142	0.0140	0.0135
Developing Country							
Welfare gain							
from $\hat{t}_Y$	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
from $\hat{t}_D$	0.0096	0.0096	0.0096	0.0096	0.0096	0.0096	0.0096

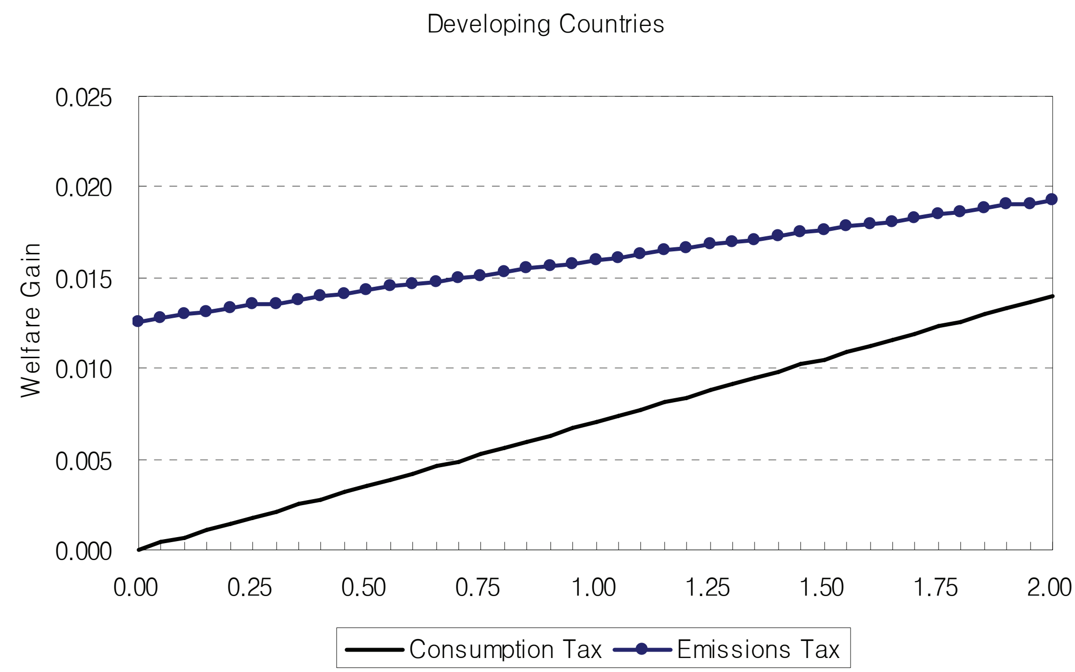
Table 1.4 above and Figures 1.1~1.3 below show how the size of the welfare gains depends on the assumptions on these parameter values.

For σ_Q, the welfare gain from either $\hat{t}_Y$ or $\hat{t}_D$ increases for both developing and developed countries as the substitution ability between outputs increases. However, the gap becomes smaller as σ_Q increases. For example, the welfare gains from $\hat{t}_Y$ and $\hat{t}_D$ are same with each other when $\sigma_Q = 2.00$ for developed countries (See Figure 1.1). This suggests that the welfare effects from the use of the environmental output taxes could be close to the welfare gain from an ideal Pigouvian tax if the substitution in consumption is large enough. For the welfare gain from $\hat{t}_Y$ and $\hat{t}_D$ to be same with each other for developing countries, the substitution in consumption would be very large. This suggests that, if the substitutability between consumption goods is not large in developing countries, the potential welfare loss from not being able to use an ideal Pigouvian tax (and instead using consumption tax instead) would be larger than developed countries.

The welfare gain also increases as σ_Y increases. Moreover, the relative strength of $\hat{t}_D$ over $\hat{t}_Y$ becomes larger as σ_Y increases. For the extreme case, if σ_Y is very small, then the welfare gain from the use of $\hat{t}_D$ could be smaller than the welfare gain from $\hat{t}_Y$. However, the result that developing countries have larger potential welfare loss from not being able to use t_D are still valid (and even strengthened) as σ_Y increases (See Figure 1.2).

As the elasticity of market labor supply (ε) increases, the welfare effects slightly decrease for developing country. This is because the household decreases market labor supply due to the decrease in real wage from a marginal increase in either t_Y or t_D. Note that the size of ε has no effects on welfare for the developed country. However, this is because the developed country has no pre-existing t_Y or t_D. In this case, the effects from the changes in ε are incidentally cancelled out from both numerator and denominator in welfare expression. If t_Y is non-zero, then the welfare effects follow more or less the same pattern as in the developing country (See Figure 1.3).

Figure 1.1: Sensitivity Analysis for Substitution Elasticiy between Outputs



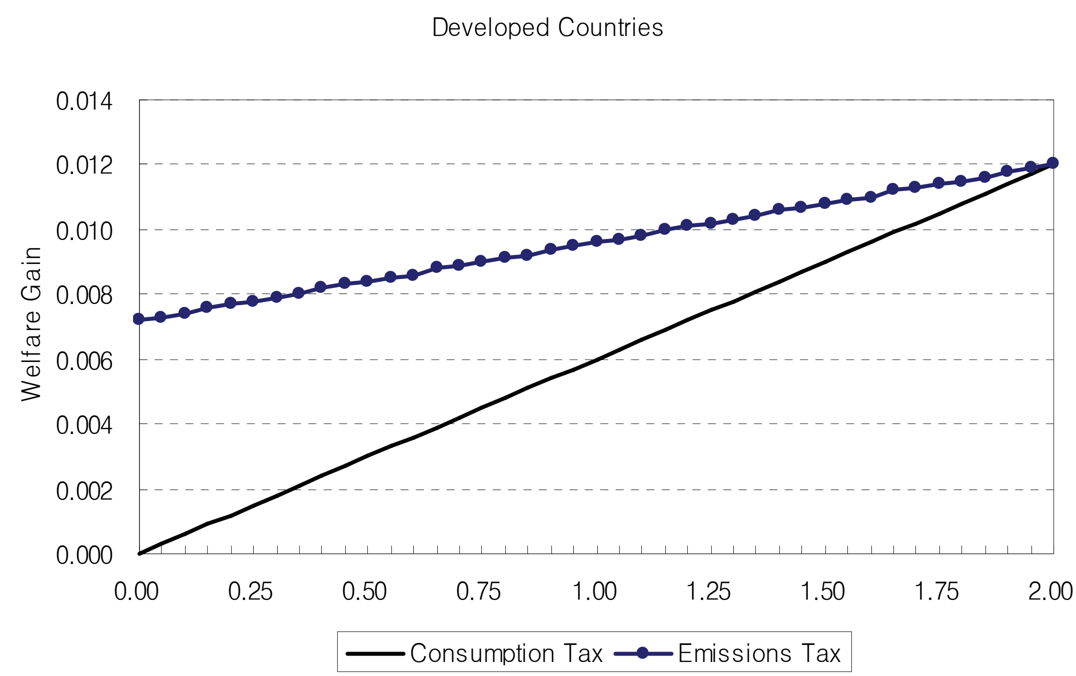
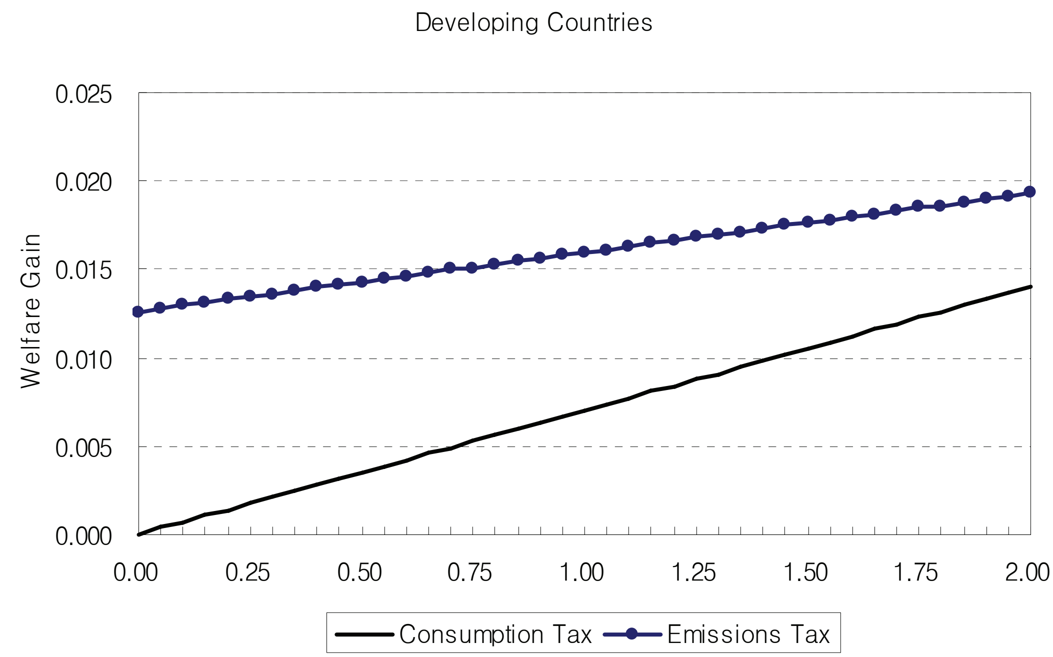


Figure 1.2: Sensitivity Analysis for Substitution Elasticiy between Inputs



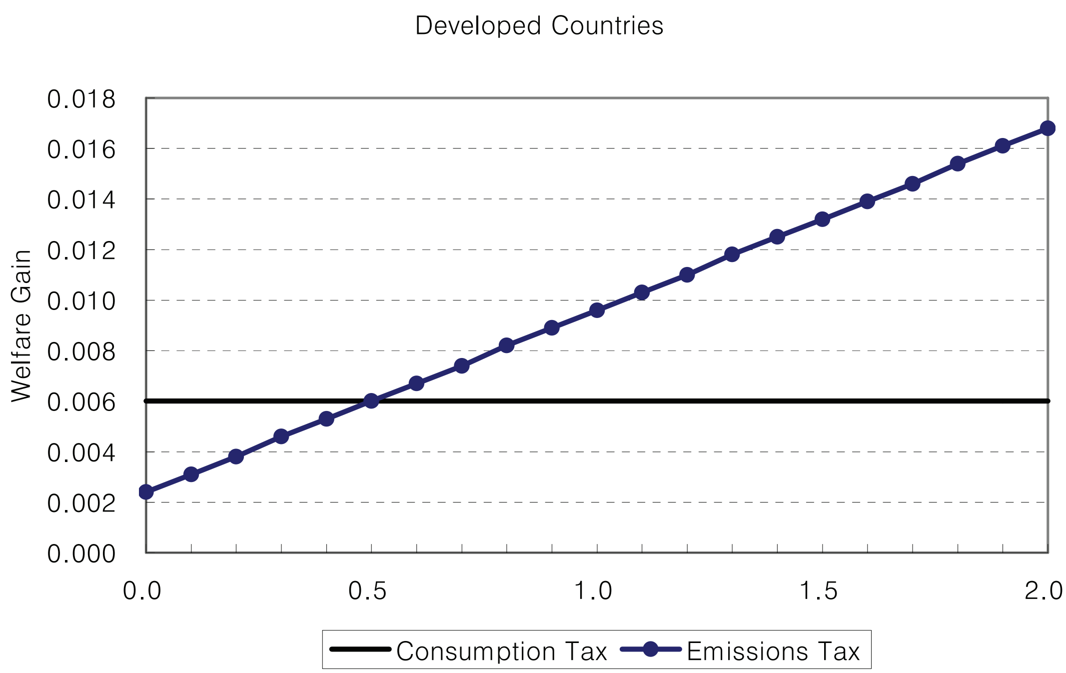
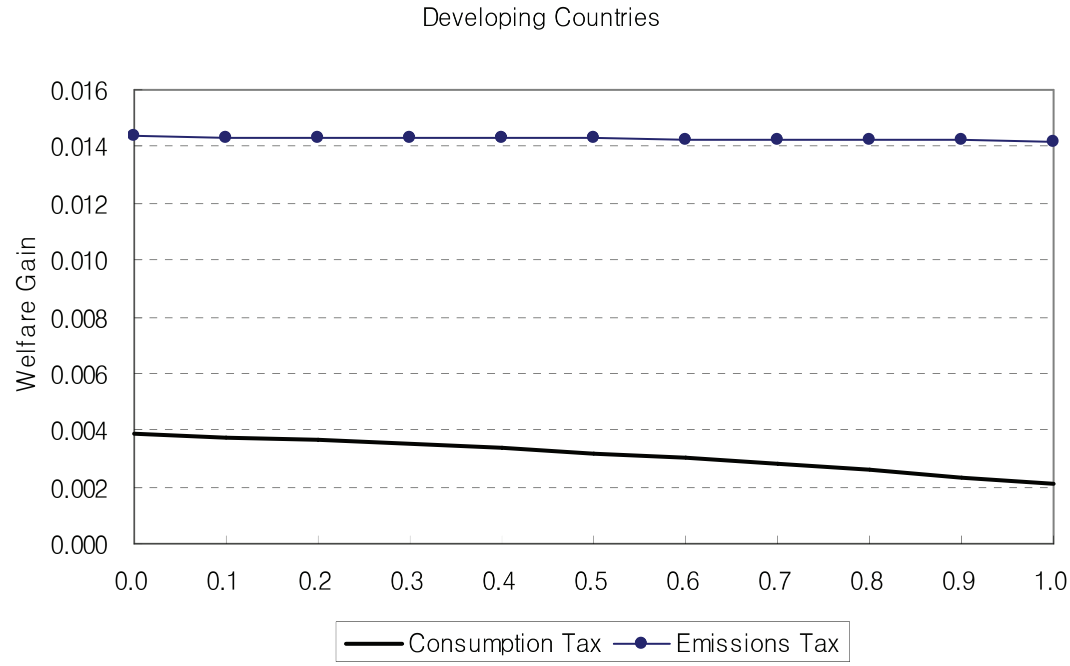
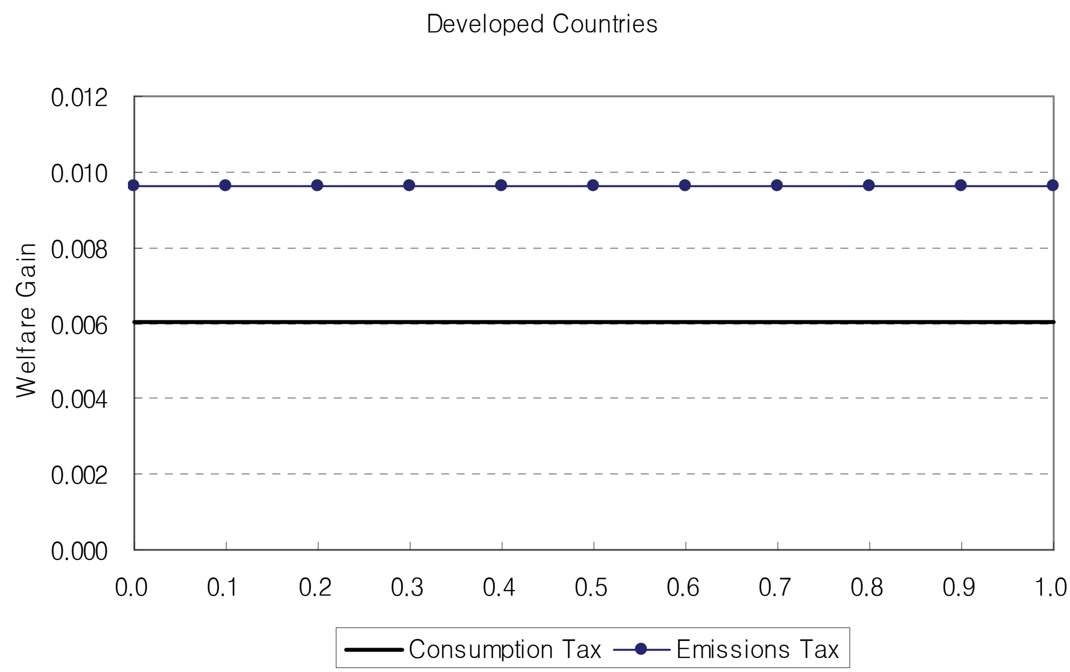


Figure 1.3: Sensitivity Analysis for Labor Supply Elasticiy





1.7 CONCLUSION

In this chapter, I use a simple general equilibrium model to examine how structural and institutional constraints might affect the relative performances of an ideal Pigouvian tax and an environmental output tax in developing countries. Although a Pigouvian tax has been shown theoretically to correct numerous environmental problems, many surveys reveal that most actual environmental taxes being used in many countries are applied to the output of a polluting industry (or to an input that is correlated with emissions).

This chapter shows theoretically that a Pigouvian tax is superior to an output tax in welfare terms, because it provides the substitution effect among inputs as well as the output effect. However, the introduction of an ideal Pigouvian tax is usually not practical, due to administrative and informational problems. These problems are much more severe in developing countries. Furthermore, many developing countries suffer from other structural constraints such as high marginal environmental damages, large traditional (and often non-taxable) sectors, a larger proportion of polluting industries in total output, and many out-dated and polluting production technologies. Due to these additional constraints, developing countries might experience larger potential welfare disadvantages from not being able to use Pigouvian taxes.

With a set of parameter values from China, which is believed to have many structural characteristics in common with developing countries, this chapter shows that the net welfare gain from the use of a Pigouvian tax could be *four* times larger than that of an output tax. Moreover, the potential welfare disadvantage from not being able to use an ideal Pigouvian tax is greater in developing countries than in developed countries. This result suggests that development of policy instruments that are more accurately connected to polluting behavior is more urgent in developing countries. Furthermore, this potential welfare disadvantage implies that developing countries' efforts in various structural reforms have important effects on the welfare outcomes of their environmental policies. Moreover, this welfare disadvantage does not imply that developing countries should avoid using environmental tax instruments. Although an introduction of an environmental output tax offers a smaller welfare gain in developing countries than in developed countries, the welfare gain from output tax instruments might be substantial, considering the potential savings from monitoring and enforcement activities.

My results here concern welfare cost of having no Pigouvian tax. My model evaluates the output tax as a policy that can be implemented more easily than emissions tax. For actual environmental policy, however, governments might choose CAC policy instruments rather than output tax. When ideal tax is not available, countries use other CAC rules or non-market policies. And this tendency might be stronger in developing countries. Some forms of mandate such as a quantity restriction on pollution or certain equipment requirement might be chosen instead of emissions tax. My model in this chapter does not explicitly consider this point. Under competitive conditions, market-based instruments usually perform better than CAC. In the presence of market imperfections, however, the effectiveness of the different policy instruments is ambiguous (Raquate, 2005). As shown by Fullerton and Metcalf (2001), the effectiveness of welfare improving environmental policy instruments comes not from its revenue-raising property: any policy instruments that generat privately-retained scarcity rents exacerbate the pre-existing labor tax distortion. In this sense, my model can be further modified to consider what structural and institutional characteristics in developing countries are important in generating privately-held scarcity rents. In one hand, many developing countries suffer from not too transparent law-making as well as enforcement problems. For example, corruption tends to increase scarcity rents. On the other hand, any organized objections to delay adoption of market-based environmental policy instruments and to maintain scarcity rents might be weaker in developing countries. Formalization of these points into my model following Fullerton and Metcalf (2001) would be one of several possible extensions of my paper.

Other research questions not examined in this chapter represent important directions for further study. First, this chapter considers a tax on output of the polluting (and taxable) industry, for comparison with the ideal Pigouvian tax. However, some of the actual environmental taxes apply to an input to production that is correlated with emissions. To analyze such a tax, the model in this chapter could be modified such that the polluting industry uses three inputs to production: labor, emissions, and some other input that is correlated with emissions.

I also note that this chapter relies on many other standard simplifying assumptions such as a closed economy with perfect certainty and perfect competition, homogeneity among firms and households, and no trans-boundary pollution.

Even though a closed economy model is an adequate representation of China, many developing countries are smaller and more open than China. On the other hand, one might vary the assumption of perfect competition, because the state and collectives own many enterprises in Chinese industry, even though their importance has been reduced.

Chapter 2

Two Reasons to Subsidize Household Recycling: The Effects of Imperfect Recycling and Reprocessing on the Optimal Recycling Subsidy

2.1 INTRODUCTION

In recent years, environmental concerns about generation and disposal of waste have greatly increased. As of 2005, more than 245 million tons of municipal solid waste (MSW) was generated in the United States alone, which was 208 million tons in 1995 (US EPA, 2002 and 2007). This means that each person generated an average of 4.5 pounds of solid waste per day and the situation is not much different in other developed countries. In developing countries, each person presently generates less than 2 pounds of waste per day. Rapid urbanization along with economic development, however, suggests that their waste generation and disposal problems will become more serious in the near future (World Bank, 1999).

Economic theory suggests that a regulator can achieve the social optimum by imposing a tax on waste-generating activity or by subsidizing its reduction (Pigou, 1932). A direct application of this approach to the MSW problem is the per-unit charge, the practice of charging waste generators for each bag or container of trash. If the per-unit charge on disposal is equal to the sum of the marginal private cost of waste collection and disposal plus any environmental externalities, and if it is perfectly enforceable, then the resulting level of MSW disposal will be optimal (Jenkins, 1993). However, it is practically impossible to tax the polluting activity directly because the informational burden is stiff and, therefore, administrative and enforcement costs would be huge.[25] Furthermore, these charges can make the environmental problems worse if the possibility of illegal disposal is real.[26] In that case, introduction of unit-pricing policy might increase illegal dumping or burning (Fullerton and Kinnaman, 1995; Sigman, 1995).[27] Another important weakness of unit-pricing policy is that its price elasticity might be quite low.[28] Even after the introduction of unit-pricing, the reduction of MSW tends to be small in many cases (Yoshida, 2002).[29]

Without an enforceable Pigouvian tax or collection charge, many studies show that a combination of output tax and recycling subsidy, also known as a deposit-refund (D-R) system, can achieve the first-best outcome. For example, using a general equilibrium model, Fullerton and Kinnaman (1995) show that the optimal D-R system consists of an output tax combined with a subsidy for recycling, and for proper garbage disposal, with each rate set on the basis of the marginal social cost of disposal.[30] In the process, recycling has drawn great attention from many researchers due to its roles in waste management.[31]

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25 If the low-income households generate a large proportion of waste from less recyclable materials such as food residuals, compared to high-income households, the per-unit charge would be regressive in terms of income redistribution. This tendency might become worse if the waste pickup services as well as any recycling facilities were not well-organized in the low-income areas, since recycling efforts would be less effective.

26 See US EPA (1998) about why illegal dumping is a problem.

27 Choe and Fraser (1999) also show that the first-best optimal tax on waste cannot be achieved when household waste reduction effort is significant and possibility of illegal waste disposal exists.

28 Several empirical studies have measured the price elasticity in various ways. Although the results are varied, many studies show quite low price elasticity. See, in particular, Choe and Fraser (1998).

29 Note that it might have resulted from the low charge rates for MSW collection adopted by many municipalities.

30 Fullerton and Wolverton (1999) confirm this result under more general settings. The "two-part instrument" is a generalized form of deposit-refund system that uses output taxes combined with subsidies to any kinds of pollution abatement activities such as substitution to cleaner inputs, legal disposal, and recycling. Walls and Palmer (2001) also show similar results using partial equilibrium models.

31 For example, Fullerton and Wu (1998) explicitly introduce two product-design variables into their model: packaging per unit output and recyclability. They show that the social optimum can be achieved if

Previous studies, however, have mainly focused on a single aspect of recycling: households' garbage reduction effort by recycling. Recycling is often assumed perfect in the sense that any recycled materials by households can be perfectly substitutable as an input for production. For example, both Fullerton and Kinnaman (1995) and Fullerton and Wu (1998) implicitly assume recycling as a costless household activity of separating or decomposing consumption waste.[32]

In this chapter, household recycling is not perfect. Household recycles usually need treatment or reprocessing to be used later for the production of consumption goods. For example, post-consumer recycling of plastics is complicated because it is often confusing to tell apart one type from another by sight or touch. Many households usually collect plastics without considering their exact types. Even a small amount of the wrong type of plastic can ruin the whole melt. Therefore, in my model, recycling *per se* is not final in reducing waste permanently; only the proportion properly reprocessed and used in successive stages of production contributes to reduction in waste. For example, any mixed plastics and wet newspapers are useless or too expensive to salvage for reprocessing firms. Therefore, I assume that only properly reprocessed recycles can be used in production, and I explicitly take account of this point by separating reprocessing from recycling.

Second, previous literature also usually assumes that reprocessing is perfect. However, reprocessing costs private resources and, more often than not, generates waste. Reprocessing waste or pollution could be just any residuals unsuccessfully

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consumers are properly charged for their garbage disposal with a "downstream" tax on waste disposal. Even if a Pigouvian tax for disposal is not available, welfare can still be improved with proper "upstream" instruments such as a subsidy to recycling or to recyclability. Walls and Palmer (2001) similarly examine the role of an advance disposal fee in the context of life-cycle assessments. As in Fullerton and Kinnaman (1995), both studies find that the first-best outcome can be achieved with various combinations of policy instruments in the context of possible market failures.

[32] Walls and Palmer (2001) also take the same approach.

reprocessed from household recyclables or might be generated due to the inherent technological limits in reprocessing. For example, waste oil (used motor oil from cars) can be reused after proper reprocessing treatment, but it would generate impurities that have to be disposed after reprocessing. Waste tires, after taken off cars, can be used as fuel because they have very high BTU. However, burning waste tires generate several toxic gases.

Other studies have also identified these aspects but examined them differently from my model. In particular, Eichner and Pethig (2001) consider the case that producers can change material mix of a final good by product design. One of these materials is recyclable, and a greater recyclable share in the output makes it easier to recover and reuse the material. They acknowledge that recycling of material is necessarily incomplete. They allow for the possibility that this "waste material" is environmentally harmful after recycling, and that reprocessing is not completely substitutable. They focus their attention to the "material content" of products, which is a more limited form of product design. They do not distinguish two different kinds of imperfection between recycling and reprocessing, either. On the other hand, Calcott and Walls (2002) take into account the transaction costs associated with recycling markets. They model recyclability as an index that affects the cost of reprocessing household recycles. However, my model takes into account not only costly reprocessing but also externalities from reprocessing.

Using a simple analytical general equilibrium model based on Fullerton and Kinnaman (1995), I solve for the combinations of tax-subsidy instruments that achieve the first-best social optimum. I also examine what roles household recycling have in remedying the negative externalities from various sources, and how imperfection of recycling and reprocessing built into the model affects the characteristics of a generalized optimal D-R system adopting the two-part instrument.

If the first-best Pigouvian taxes are available, then the optimal corrective tax on each activity causing a negative externality is equal to its marginal environmental damages (MED). In this case, other output and input taxes are not necessary. And a subsidy for household recycling is also unnecessary because recycling improves (or harms) the environment only through successful reprocessing. Since the reprocessing externality is corrected by an existing Pigouvian tax, recycling is neither rewarded nor penalized.

If illegal disposal or dumping cannot be properly taxed due to monitoring and enforcement problems, that is, if a Pigouvian tax on illegal disposal is not feasible, then a combination of a presumptive output tax and the corresponding subsidies for proper garbage disposal and for household recycling is optimal (a two-part instrument). In this case, a charge on garbage disposal should be lowered by the extent that proper disposal diverts illegal dumping. The important point is that a recycling subsidy is also needed because recycling also diverts illegal dumping to proper disposal. This is the first reason to subsizie household recycling and it is first successfully derived in Fullerton and Kinnaman (1996).

My contribution is to add another (second) reason to subsidize household recycling by considering the imperfection in recycling as well as in reprocessing. If no Pigouvian tax is available on the waste from imperfect reprocessing, then the role of recycling becomes more important. Now recycling receives a subsidy for two different reasons: the first from the role that diverts illegal disposal as noted earlier. The second part of a recycling subsidy comes from the imperfection assumption regarding reprocessing. In the absence of a Pigouvian tax on reprocessing waste, an additional "two-part instrument" should be implemented. In this case, it consists of a presumptive output tax on reprocessed material and the subsidies for labor and for household recycling. Again, this imperfection factor in recycling does not change the importance of a recycling subsidy: it can be handled by a charge for proper garbage disposal. But the fact that reprocessing is imperfect can only be handled by a subsidy for recycling when a first-best Pigouvian tax on waste from reprocessing is not available.

Before presenting the model in the next section, it would be helpful to clarify my two terminologies: imperfect recycling and imperfect reprocessing. By 'imperfect recycling,' I mean that the recycling activities by households are partial. It could be so because households do not always know how to correctly recycle many different materials. By 'imperfect reprocessing,' I mean that the reprocessing technology is not perfect.

In the following Section 2.2, I introduce the model. In Section 2.3, I derive the outcome in the social planning model as well as the decentralized market outcome. Then, I compare the decentralized outcome with the social planner's and derive the first-best optimal tax-subsidy schemes, first assuming that a Pigouvian tax on the use of reprocessed materials is available and then relaxing that assumption. Finally, Section 2.4 is for conclusion and further discussion.

2.2 THE MODEL

My model is a simple general equilibrium model. It is also a first-best model, since it does not incorporate any other distorting taxes on labor supply or capital. I use lower case letters to denote values per household and upper case letters for aggregates.

I consider a single jurisdiction with n identical households. Each buys a single composite consumption good c, and each disposes of solid waste in three forms: proper garbage collection g, potentially recyclable materials r, or illicit burning or dumping b. These alternatives are substitutes in the technology of household of disposal options.

$$c = d(g, \quad r, \quad b), \tag{2.1}$$

where $d(\bullet)$ is continuous and quasi-concave, with first derivatives $d_g > 0$, $d_r > 0$, and $d_b > 0$. That is, all three kinds of disposal by households can increase the quantity of consumption c. This relationship also depicts how the household is able to shift among disposal methods. With a given amount of consumption, the household may be able to reduce g and/or increase r by engaging in various activities such as collecting plastic and newspapers and/or increase b by burning garbage in her backyard or dumping them in public places. Therefore, Eq. (2.1) relates all the different combinations of g, r, and b that are consistent with any given level of consumption (like an isoquant).

The household has a fixed total of resources k (which can be labor, capital, or both). Though these illegal activities do not incur any costs in terms of market price, they are assumed to use private resources $k_b = \beta(b)$. The marginal costs of burning are assumed positive $(\beta_b > 0)$ and rising $(\beta_{bb} > 0)$.

In the household garbage collection industry, firms use resources, k_g, as the only input with a linear production technology:

$$g = \gamma k_g . \tag{2.2}$$

Firms extracting virgin materials produce v, use resources k_v, and generate pollution w_v with a constant returns to scale technology:

$$v = v\left(k_v, \quad w_v\right), \tag{2.3}$$

with both first derivatives v_{kv} and v_{wv} positive. Thus, firms have to use more input materials and/or allow more pollution to produce more virgin materials.

Reprocessing firms collect potentially recyclable materials r from households, reprocess it into reprocessed material m, and supply m to the producers of the consumption good. In doing so, they use resources k_m and generate reprocessing waste w_m:

$$m = m\left(k_m, \quad r, \quad w_m\right), \tag{2.4}$$

with all the first derivatives m_{km}, m_r, and m_{wm} positive. Note that, like firms in extracting virgin materials, reprocessing firms can increase output if they increase pollution from reprocessing (w_m) or any other input. Previous literature usually assumes that household recycling is complete and final, so that any recycled materials can be used as inputs for production without further waste. However, recycled materials by households usually require treatment or reprocessing to be used later for the production of consumption goods.

The consumption good c is produced using a constant returns to scale production function

$$c = f\left(k_c, \quad v, \quad m\right), \tag{2.5}$$

with input of resources k_c, virgin materials v, and reprocessed materials m.[33] Since all production functions are constant returns to scale, the scale of the firm is irrelevant. Thus, I can assume that each symbol above represents an amount per capita.

Utility of each individual depends positively on the amount of consumption good purchased in the market (c) and leisure use of time and resources $(l = k_l)$. It depends negatively on the total amount of garbage generated by households $(G \equiv ng)$, the total amount of pollution generated in the production of virgin material $(W_v \equiv nw_v)$, and the aggregate pollution generated in the production of reprocessed material $(W_m \equiv nw_m)$.[34] Utility also depends on the aggregate pollution generated by illegal burning or dumping $(B \equiv nb)$. These four negative externalities could require four Pigouvian taxes. If any one such Pigouvian tax is not available, it can be replaced by a two-part instrument. Some of those two-part instruments might imply a subsidy to recycling, and some might not.

The utility function is

$$u = u\left(c,\ l,\ G,\ B,\ W_v,\ W_m\right), \tag{2.6}$$

where the first derivatives are $u_c > 0$, $u_l > 0$, $u_G < 0$, $u_B < 0$, $u_{Wv} < 0$ and $u_{Wm} < 0$. I also assume that the MED from illegal disposal or dumping exceeds that from proper disposal $(u_G > u_B)$.[35] This assumption seems innocuous: for

[33] Note that the above production function (2.5) is general with respect to the relation between v and m. For example, this production function includes a special case where virgin and reprocessed recycled materials are homogeneous in quality and, therefore, can be used as a perfect substitute for each other: $c = f\left(k_c,\ v + m\right)$.

[34] Extraction of virgin materials may reduce the utility of others. For example, cutting timber may reduce the enjoyment of natural areas and possibly aggravate global warming (Fullerton and Kinnaman, 1995).

[35] For example, *The Economist* (1993) reports that the costs incurred by illegal burning or dumping are significantly greater than the costs of proper landfilling.

example, the contamination of the water supply polluted by waste dumped in unsafe pits and the air pollution caused by illegal burning aggravate the social health and clean-up problems, more-so than proper disposal of garbage in a landfill (Ferrara, 2003).

Note that the utility function has four different types of waste that all affect utility differently. Hence, my model is more general than having only one waste externality in utility. This feature is useful to show what happens in the special cases where all add to the same externality. Also, the different types of externalities from waste help clarify what happens in my results with optimal taxes and subsidies. This point will be discussed with the analytical results later.

Finally, the model is closed by the overall resource constraint:

$$k = k_c + k_l + k_g + k_b + k_m + k_v. \tag{2.7}$$

2.2.1 Outcome in the social planner's problem

The social planner maximizes the utility of the representative household in (2.6) subject to the social planner's constraint (2.5) that is reformularized with the resource constraint and production functions (2.1) and (2.7). The resource and production constraints can be substituted directly, to maximize the appropriate Lagrangian:

$$\begin{aligned} \mathcal{L} \;=\; & u\Big[d\big(\gamma k_g,\ r,\ b\big),\ k_l,\ n\gamma k_g,\ nb,\ nw_m,\ nw_v\Big] \\ & + \delta\left[f\left(\begin{array}{c} k - k_l - k_g - k_m - k_v - \beta(b), \\ v\big(k_v,\ w_v\big),\ m\big(k_m,\ r,\ w_m\big) \end{array} \right) - d\big(\gamma k_g,\ r,\ b\big) \right] \end{aligned}$$

with respect to r, b, k_g, k_l, k_v, k_m, w_v, and w_m. I assume that a unique and internal solution exists. The first-order conditions are

$$u_c d_g + u_G n = \delta\left(\frac{f_{kc}}{\gamma} + d_g\right), \tag{2.8a}$$

$$u_c d_r = \delta\left(d_r - f_m m_r\right), \tag{2.8b}$$

$$u_c d_b + u_B n = \delta\left(f_{kc}\beta_b + d_b\right), \tag{2.8c}$$

$$u_l = \delta f_{kc}, \tag{2.8d}$$

$$u_{Wm} n = -\delta f_m m_{wm}, \tag{2.8e}$$

$$u_{Wv} = -\delta f_v v_{wv}, \tag{2.8f}$$

$$f_{kc} = f_m m_{km}, \tag{2.8g}$$

and

$$f_{kc} = f_v v_{kv}, \tag{2.8h}$$

where δ denotes the social marginal utility of income, f_{kc} is the marginal product of k used in the production of consumption good (c), f_m is the marginal product of reprocessed materials (m), f_v indicates the marginal products of virgin materials (v), and m_{km} is the marginal product of k_m used in reprocessing.

Equations (2.8a~2.8h) state that each input should be employed up to the point where its marginal social benefit equals its marginal social cost. In (2.8a), for instance, the dollar value of utility from consumption made possible by a unit of garbage $\left({u_c d_g}/{\delta}\right)$ is reduced by the utility cost of the garbage externality $\left({u_G n}/{\delta}\right)$ before comparison with the production cost of garbage.

2.2.2 Outcome in the decentralized model

For the case of private markets, individuals maximize utility in (2.6) subject to a budget constraint that may be affected by a tax or subsidy on each good,

$$\begin{aligned} & p_k\left(k - k_l - \beta(b)\right) + \left(p_r - t_r\right) r \\ & = \left(1 + t_c\right) \cdot d(g,\ r,\ b) + \left(p_g + t_g\right) g + t_b \cdot b, \end{aligned} \tag{2.9}$$

where p_k is the price earned on resources, the price of consumption good equals one $\left(p_c = 1\right)$ since c is numeraire, t_c is the tax per unit of consumption, p_g is the price paid by households for garbage collection, t_g is the tax per unit of garbage, p_r is the price for recyclables paid by the reprocessing firms to the households (which could be positive or negative), t_r is the tax on (or subsidy for) the household per unit of potentially recyclable materials collected by the household, and t_b is an ideal Pigouvian tax on illegal disposal.[36] Note that the private cost of illegal disposal, $p_k\beta(b)$, is included in the budget constraint.

Consumption goods producers receive a price $\left(p_c = 1\right)$ for selling c and pay for inputs k_c, v, and m. Their profits are expressed as follows:

$$\pi^c = f\left(k_c,\ v,\ m\right) - \left(p_k + t_{kc}\right) k_c - \left(p_v + t_v\right) v - \left(p_m + t_m\right) m,$$

where t_{kc} is the tax on the resources $\left(k_c\right)$ used in production of consumption good, p_v is the price paid for virgin materials, t_v is the tax per unit of virgin materials, p_m is the price of reprocessed materials, and t_m is the tax per unit of household

[36] A tax on illegal disposal $\left(t_b\right)$ is included in (2.9) for the standard case of the first-best Pigouvian taxes. It can be set to zero for more realistic cases.

recycling. Under perfect competition with constant returns to scale, maximization of π^c gives

$$f_{kc} = p_k + t_{kc}, \tag{2.10a}$$

$$f_v = p_v + t_v, \tag{2.10b}$$

and

$$f_m = p_m + t_m. \tag{2.10c}$$

Producers of household garbage collection services similarly maximize their profits $\pi^g = p_g \gamma k_g - p_k k_g$, and the first-order condition is $\gamma p_g = p_k$. Substituting (2.10a):

$$p_g = \frac{f_{kc} - t_{kc}}{\gamma}. \tag{2.11}$$

For reprocessing firms, the following profit function is maximized: $\pi^m = p_m \cdot m(k_r,\ m,\ w_m) - (p_k + t_{km})k_m - p_r r - t_{wm} w_m$. Using (2.10a) and (2.10c), the first-order conditions can be simplified as follows:

$$(f_m - t_m)m_{km} = f_{kc} - t_{kc} + t_{km}, \tag{2.12a}$$

$$(f_m - t_m)m_r = p_r, \tag{2.12b}$$

and

$$(f_m - t_m)m_{wm} = t_{wm}. \tag{2.12c}$$

Finally, producers of virgin materials maximize $\pi^v = p_v \cdot v(k_v,\ w_v) - (p_k + t_{kv})k_v - t_{wv} w_v$. Using (2.10a) and (2.10b) to simplify the first-order conditions:

$$\left(f_v - t_v\right) v_{kv} = f_{kc} - t_{kc} + t_{kv} \tag{2.13a}$$

and
$$\left(f_v - t_v\right) v_{wv} = t_{wv} . \tag{2.13b}$$

In this decentralized economy, the consumer chooses g, r, b, and l to maximize utility in (2.6) subject to the budget constraint in (2.9). The resulting four first-order conditions involve prices (p_k, p_g, and p_r), but I replace those with marginal products from (2.10a), (2.11), and (2.12b) to get (2.14a~2.14d). The consumer's lagrangian multiplier μ denotes the private marginal utility of income. Four other conditions for the decentralized equilibrium (2.14e~2.14h) come from various profit maximizations.

$$u_c d_g = \mu\left[\left(1 + t_c\right) d_g + \frac{f_{kc} - t_{kc}}{\gamma} + t_g\right], \tag{2.14a}$$

$$u_c d_r = \mu\left[\left(1 + t_c\right) d_r + t_r - \left(f_m - t_m\right) m_r\right], \tag{2.14b}$$

$$u_c d_b = \mu\left[\left(1 + t_c\right) d_b + \left(f_{kc} - t_{kc}\right) \beta_b + t_b\right], \tag{2.14c}$$

$$u_l = \mu\left(f_{kc} - t_{kc}\right), \tag{2.14d}$$

$$t_{wm} = \left(f_m - t_m\right) m_{wm} , \tag{2.14e}$$

$$t_{wv} = \left(f_v - t_v\right) v_{wv} , \tag{2.14f}$$

$$f_{kc} - t_{kc} + t_{km} = \left(f_m - t_m\right) m_{km} , \tag{2.14g}$$

and
$$f_{kc} - t_{kc} + t_{kv} = \left(f_v - t_v\right) v_{kv} . \tag{2.14h}$$

Now I can find the optimal tax and subsidy rates in equations (2.14) that make those market conditions in (2.14) match up perfectly with the social planner's conditions in (2.8).

2.3 OPTIMAL POLICIES FOR THE FIRST-BEST OUTCOMES

2.3.1 When the first-best Pigouvian taxes are available.

If the market does achieve the optimum, then $\delta = \mu$ from (2.8d) and (2.14d). By comparison of (2.8) and (2.14), if $t_c^* = t_m^* = t_v^* = t_r^* = t_{kc}^* = t_{km}^* = t_{kv}^* = 0$, then:

$$t_g^* = -\frac{u_G n}{\mu},$$

$$t_b^* = -\frac{u_B n}{\mu},$$

$$t_{wm}^* = -\frac{u_{Wm} n}{\mu}, \tag{2.15}$$

and

$$t_{wv}^* = -\frac{u_{Wv} n}{\mu}.$$

This is the standard result from the general principle of Pigou (1932): the optimal corrective tax on an activity causing a negative externality is equal to its MED. Therefore, any output or input taxes become unnecessary if the first-best Pigouvian taxes are available. Note that the tax on household recycling $\left(t_r^*\right)$ is zero. Household recycling itself has no external effect. It improves (or harms) the environment only through reprocessing. Since any waste generated by reprocessing firms is already taxed $\left(t_{wm} > 0\right)$ according to its damage to the environment, household recycling is neither rewarded nor penalized.

Note that the first-best optimal taxes on virgin waste (W_v) and on reprocessing waste (W_m) can be collapsed into a single optimal tax on waste (t_w), if there is no difference between household recycling and reprocessing.

Can the environmental authority estimate the necessary quantity restrictions from these results and implement the command and control policies such as mandatory recycling for households and/or minimum recycled-content standards on producers in order to achieve socially efficient outcomes? At least in theory, it appears to be possible. As Palmer and Walls (1997) show, however, such standards by themselves can achieve the social optimum only when combined with additional taxes on both the final product and other inputs. Furthermore, the information burden required to achieve those efficient outcomes would be huge, and so this information is not likely to be available to policymakers.

It is not certain if illegal disposal increases after introducing a tax on garbage pickup services. On one hand, some studies report that this was indeed the case, especially in the densely populated urban areas of the city.[37] On the other hand, there exist other studies that report the contrary.[38] Even if illegal disposal was initially caused by the imposition of a price on garbage, it might not long remain a serious problem (OECD, 2004).

2.3.2 When illegal disposal cannot be taxed

The first-best Pigouvian taxes on disposal derived in the previous subsection 2.3.1 is generally considered to be impractical. In particular, a simple Pigouvian tax on

[37] See, for example, Reschovsky and Stone (1994) and Fullerton and Kinnaman (1996).
[38] See, for example, Miranda and LaPalme (1997) and Nestor and Podolsky (1998).

illegal burning or dumping $\left(t_b^*\right)$ is difficult, if not impossible, to implement due to monitoring and enforcement problems. If t_b^* is not available, then the social optimum can still be achieved by using a combination of a presumptive tax on consumption and a subsidy for proper disposal activities (g and r) as follows. If $t_b^{**} = t_m^{**} = t_v^{**} = t_{kc}^{**} = t_{km}^{**} = t_{kv}^{**} = 0$, then:

$$t_c^{**} = -\frac{u_B n}{\mu c_b},$$

$$t_g^{**} = -\frac{u_G n d_g}{\mu d_b} + \frac{u_B n d_g}{\mu d_b},$$

$$t_r^{**} = \frac{u_B n d_r}{\mu d_b}, \tag{2.16}$$

$$t_{wm}^{**} = -\frac{u_{Wm} n}{\mu},$$

and
$$t_{wv}^{**} = -\frac{u_{Wv} n}{\mu}.$$

Since $u_B < 0$, the presumptive consumption tax $\left(t_c^{**}\right)$ is positive and it reflects the MED from illegal disposal $\left(-u_B n \big/ \mu d_b\right)$. Garbage is taxed for its detrimental effects on the environment $\left(-u_G n d_g \big/ \mu d_b > 0\right)$ but this proper garbage disposal is subsidized $\left(u_B n d_g \big/ \mu d_b < 0\right)$ to avert illegal disposal. This result clearly shows that if the corresponding first-best Pigouvian tax is not available due to various difficulties, a combination of proper "two-part instruments" can be used instead (Fullerton and Wolverton, 1999).

It is evident that the disposal fee is less than the Pigouvian charge derived in the previous subsection $\left(t_g^{**} < t_g^*\right)$ because of the negative second term $\left({u_B n d_g}/{\mu d_b}\right)$. It is not easy to determine, however, how much t_g^{**} would be lower than t_g^*. If the MED from illegal disposal is large enough, then the optimal charge for garbage pickup might approach zero or, in extreme case, turns out negative. The ultimate level and/or sign of t_g^{**} also depends on the relative easiness of illegal burning to proper garbage collection (d_b and d_g).[39] If proper garbage pickup systems are not readily available (i.e., high d_g) or unsafe garbage disposal is wide-spread (i.e., low d_b) as in many developing countries, free garbage pickup services may be more effective in improving environmental welfare.[40]

Note that the tax on household recycling $\left(t_r^{**}\right)$ is negative (i.e., a subsidy). In the previous subsection, $t_r^* = 0$ since recycling was not held responsible for being either detrimental or beneficial to the environment and the environmental authority could remedy the four externalities with the four Pigouvian taxes (t_g^*, t_b^*, t_{wm}^*, and t_{wv}^*). In the absence of any t_b, however, household recycling contributes to proper waste disposal by diverting illegal burning or dumping. Therefore, household recycling is subsidized to the extent of its contribution.

Also note that the optimal tax on waste from extracting virgin material $\left(t_{wv}^{**}\right)$ is exactly equal to the MED caused by this activity: it is not used to encourage recycling or to discourage the generation of waste. Therefore, the environmental authority should not attempt to use this upstream tax to solve the externalities from downstream activity.

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39 Consider the "material balance" case: $d = g + r + b$. Since $d_r = d_b = 1$ in this case, the optimal tax and subsidy rates in (2.16) show that garbage receives a net subsidy (because it is assumed that $u_B < u_G$).

40 This case would be also relevant in some developed countries that have vast and less-populated areas like Australia (Choe and Fraser, 1998).

These results are well-established by the previous studies including Fullerton and Kinnaman (1995) and Walls and Palmer (2001).

My model shows that the same logic can be applied to the case of a Pigouvian tax on reprocessing waste. The optimal tax on waste or pollution generated from reprocessing $\left(t_{wm}^{**}\right)$ is also exactly equal to the MED caused by reprocessing: it is not used to remedy the imperfection of household recycling or to discourage illegal dumping. This result implies that the environmental authority should not be confused between two different kinds of imperfection between household recycling and reprocessing. Household recycling should be subsidized exactly to the extent that it diverts potential illegal dumping. It should not be penalized based on any presumptive mistakes that households might cause such as placing recyclables into garbage containers. Any household recyclables sent to landfill sites due to incomplete recycling can be charged with t_g^{**}.

2.3.3 When no Pigouvian taxes are available

In practical viewpoint, it is not much easier to implement the first-best Pigouvian taxes on both reprocessing waste $\left(t_{wm}\right)$ and virgin material extraction externality $\left(t_{wv}\right)$ than a tax on illegal dumping or burning $\left(t_b\right)$. It would be difficult to monitor pollutants accurately and to enforce the optimal charges. Although this chapter primarily focuses on the optimal MSW policies, any efforts to reduce MSW are intrinsically related to other forms of pollutants such as airborne particles and sewage. These factors dramatically increase the difficulties in gathering any necessary information to calculate the optimal rates of Pigouvian taxes and in enforcing them.

Even if no Pigouvian taxes are available, however, the environmental authority still can find the appropriate first-best tax-subsidy scheme to achieve the optimum, as follows. If $t_b^{***} = t_{wm}^{***} = t_{wv}^{***} = t_{kc}^{***} = 0$, then the social planner's first-best FOC can still be satisfied if:

$$t_c^{***} = -\frac{u_B n}{\mu d_b} > 0,$$

$$t_g^{***} = -\frac{u_G n d_g}{\mu d_b} + \frac{u_B n d_g}{\mu d_b} \gtrless 0,$$

$$t_r^{***} = \frac{u_B n d_r}{\mu d_b} + \frac{u_{Wm} n m_r}{\mu m_{wm}} < 0,$$

$$t_m^{***} = -\frac{u_{Wm} n}{\mu m_{wm}} > 0, \tag{2.17}$$

$$t_v^{***} = -\frac{u_{Wv} n}{\mu v_{wv}} > 0,$$

$$t_{km}^{***} = \frac{u_{Wm} n m_{km}}{\mu m_{wm}} < 0,$$

and

$$t_{kv}^{***} = \frac{u_{Wv} n v_{kv}}{\mu v_{wv}} < 0.$$

The different waste externalities that I use in my model (i.e., $G,\ B,\ V,\ W_v,\ W_m$) help clarify what happens in the above resuts. For example, every term with U_B can be grouped conceptually, because they all are used in combination to correct for the fact that government cannot tax illegal burning or dumping. Similarly, every term with U_G can be grouped conceptually because they arll are used in combination to correct for the case that government cannot tax proper disposal of household garbage. For example, three tax rates in (2.17) have a term with U_{Wm} for waste in materials reprocessing. The production function is $m = m(k_m, \quad r, \quad W_m)$. If government cannot tax W_m, then the equivalent is to tax output m, and subsidize both other inputs k_m and r.

The optimal level of a presumptive consumption tax $\left(t_c^{***}\right)$ does not change from the one obtained in the previous subsection $\left(t_c^{**}\right)$. It is positive and reflects the MED from illegal disposal. Garbage is again taxed for its detrimental effects on the environment but this proper disposal is subsidized to avert illegal disposal. However, an output tax on reprocessed material $\left(t_m^{***} > 0\right)$ is needed to handle the externality from reprocessing waste (w_m). In this case, t_m^{***} should be combined with a subsidy for the clean input $\left(t_{km}^{***} < 0\right)$ to undertake the same role of the first-best Pigouvian tax on reprocessing waste $\left(t_{wm}^{**}\right)$ in the previous subsection. This is exactly the same logic of the "two-part instrument" that replaces the Pigouvian tax on illegal burning $\left(t_b^{***}\right)$ with a combination of the presumptive consumption tax and a recycling subsidy. Reprocessing firms are assumed to be polluting and therefore pay tax t_m^{***} in advance, but this effectively means that all inputs employed in the reprocessing industry also have to pay taxes even though not all of these inputs are polluting. Hence, in this case, the clean input k_m receives a subsidy $\left(t_{km}^{***} < 0\right)$. The same logic also applies to the case of virgin material. Producers of virgin material pay a presumptive output tax $\left(t_v^{***} > 0\right)$, but a part of this output tax is returned to the clean input as a subsidy $\left(t_{kv}^{***} < 0\right)$. These two parts together make up for the absence of a Pigouvian tax on waste from reprocessing (t_{wr}).

Also, note that the absence of t_{wm} can be replaced by the combination of a tax on m $\left(t_m^{***} > 0\right)$ and subsidy to clean inputs $(t_r^{***} < 0$ and $t_{km}^{***} < 0)$. Now the subsidy for household recycling $\left(t_r^{***} < 0\right)$ has an additional term $\left(u_{Wm} n m_r \big/ \mu m_{wm}\right)$ unlike the previous t_r^* and t_r^{**}. This additional term shows how the characteristics of reprocessing affect the subsidy structure for household recycling. The first role is that recycling can divert illegal dumping, as already shown in the previous subsection. The second and new role is that recycling serves as a clean input for the reprocessing industry and therefore should receive a portion of the presumptive output tax on reprocessed material as another clean input k_m does.

Since marginal products of both reprocessing waste and recycling (m_{wm} and m_r) are positive, the second term of t_r^{***} is negative. Therefore, $t_r^{***} < t_r^{**} < 0$. This means that a subsidy for recycling when reprocessing is imperfect should be bigger than the subsidy for recycling when reprocessing is perfect and generates no waste. Therefore, the roles of the recycling subsidy are strengthened when the first-best Pigouvian taxes cannot be used.

2.4 CONCLUSION AND FURTHER DISCUSSION

In recent years, environmental concerns about generation and disposal of MSW have greatly increased in both developed and developing countries. Economic theory suggests that the social optimum can be achieved by imposing a tax on waste-generating activity or by subsidizing its reduction. The per-unit charge on household garbage has been proposed to implement this approach and accepted by many municipalities, even though the informational burden is heavy and often the actual rates of the per-unit charge are believed to deviate from the optimal ones. Furthermore, these charges can make the environmental problems worse if the possibility of illegal disposal is present. Therefore, a D-R system has recently been in the center of discussion. In general, a presumptive output tax combined with subsidies for recycling and proper garbage disposal can achieve the social optimum in the presence of illegal disposal. Previous studies, however, have assumed that recycling is perfect in the sense that any recycled materials by households can be substitutable for virgin material without reprocessing. Furthermore, reprocessing is also usually assumed perfect in the sense that no reprocessing waste or pollution is generated during the process.

In this chapter, neither recycling nor reprocessing is assumed perfect. Using a simple general equilibrium model, I examine how the tax-subsidy structure should change as the first-best Pigouvian taxes become unavailable.

When illegal disposal or dumping cannot be properly taxed, a positive output tax combined with the corresponding subsidies for proper garbage disposal and household recycling still can achieve the social optimum. When no other Pigouvian taxes are available either, then the optimal tax rates on consumption and garbage disposal are not different from those derived earlier. New presumptive taxes on reprocessed and virgin materials should be introduced and any clean inputs are subsidized. The subsidy for recycling now consists of two parts. The first part represents the role of recycling that diverts illegal disposal. On the other hand, the second part rewards the role of household recycling as a clean input for reprocessing. In the context of previous literature, these results confirm that a generalized D-R system proves effective in remedying various externalities without depending on the use of Pigouvian taxes. This suggests that the roles of household recycling are crucial in solving the externality problems even in the case that the environmental authority cannot freely choose all policy instruments. The authority can achieve the social optimum by increasing the magnitude of a recycling subsidy accordingly as the possibility of using the Pigouvian taxes become harder.

Is it possible to implement any other tax-subsidy schemes without relying on the use of a recycling subsidy? The answer would depend on whether the environmental authority has any other policy instruments to use following the simple logic of the "two-part instrument." For example, assuming substitutability between household recycling and virgin material as well as no externalities from reprocessing, the authority can still achieve optimum by subsidizing another clean input if a subsidy for recycling is not available as shown in Fullerton and Kinnaman (1995). However, if recycling is imperfect and reprocessing generates waste as modeled here, then a subsidy for recycling becomes an indispensable instrument since the household recycling enters into both the household's consumption function and into reprocessing firms' production function.

These results appear to be quite robust with respect to various model specifications and market conditions. For example, Ferrara (2003) shows that a combination of presumptive consumption taxes and legal disposal and recycling subsidies is still needed to achieve social optimum even when both the waste stock externality and the households' heterogeneous preferences for garbage pickup frequencies are considered.[41] Considering the "transaction costs" problem associated with any large-scale recycling programs, Shinkuma (2003) finds that a D-R system is one of the three promising alternative policy schemes.[42] Similarly, Calcott and Walls (2002) find that the most encouraging policy is a modest disposal fee which is less than

[41] In addition to a uniform consumption tax and a uniform recycling subsidy, in this case, varying pickup frequencies and differential legal disposal subsidies are also required to achieve social optimum.
[42] The other two policies include the per-unit charge with an advance disposal fee and a producer take-back requirement system.

the Pigouvian tax combined with a D-R system applied to all products. In this context, further research on the "two-part instrument" with more general assumptions and wide-ranged settings would be a promising next step.

Chapter 3

Welfare Effects of the Tax Reforms in Two Vertically-Separated Oligopolies with Environmental Externality

3.1 INTRODUCTION

In a single imperfectly competitive industry, the output level is less than the competitive level due to the divergence between price and marginal cost (so called 'marginalization' distortion). If this imperfectly competitive industry is polluting, the second distortion arises from environmental externality. If this polluting oligopolistic (upstream) industry supplies its product to another (downstream) industry—in other words, if both industries are 'vertically-separated'—then an input-mix distortion in the downstream industry arises due to the marginalization distortion from the upstream industry. Furthermore, if the downstream industry is also imperfectly competitive, then another marginalization distortion arises.

It is not difficult to find markets that have these conditions. Many industries consist of only a few firms, including automobiles, iron and steel, and petroleum refining industries.[43] Among them, many are polluting and vertically-separated to other oligopolistic industries. For instance, it is well known that coal is one of the most polluting fossil fuels, and the U.S. iron and steel industry heavily relies on coal and emits various pollutants.[44] Furthermore, the U.S. iron and steel industry supplies its

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[43] For overall market structure and market power by industries in the U.S., see Hall, et al (1986).

[44] As of 1994, the U.S. iron and steel industry accounts for approximately 9 percent of all U.S. manufacturing use of energy. Nearly half of the industry's energy is derived from coal (US DOE, 2000).

product to several oligopolistic final goods producers such as automobiles and electrical and machinery equipment industries.

This chapter can be considered as an extension from—as well as a link among—various previous studies on taxation, market imperfection, and environmental externalities. However, previous studies have been mostly interested in a single oligopolistic industry.[45] When vertically-separated oligopolies were considered, the pollution problem has not been examined. Myles (1989) considers two vertically-separated industries, but only one of them is imperfectly competitive. Panzar and Sibley (1989) consider vertically-separated industries, but they focus on the optimal two-part tariff that corrects for the marginalization distortion in the downstream industry due to the upstream monopoly. Colangelo and Galmarini (2001) examine the vertically-separated oligopoly case, but their focus is on the relative advantages of value-added taxation over cascade taxation when the firms in the upstream industry produce intermediate goods. Furthermore, they only consider the importance of the downstream input substitutability, because the upstream producers have a single input and, therefore, cannot substitute between inputs.

In this chapter, I construct an analytical partical equilibrium model of two vertically-separated oligopolies where the upstream industry is polluting, and examine

[45] For example, Konishi (1990) examines the case where an oligopolistic industry producing a final good uses many intermediate goods but the intermediate goods are produced competitively. Although not an exhaustive list, the following different aspects of the topic have been studied: the case of symmetric oligopoly with a fixed number of firms and various types of technology (Ebert, 1991), the case of endogenous market structure (Katsoulacos and Xepapadeas, 1995a), endogenous entry/exit decisions (Katsoulacos and Xepapadeas, 1995b), dynamic tax/subsidy schemes when the stock of pollution accumulates over time (Benchekroun and Long, 1998), endogenous product quality (Cremer and Thisse, 1999; Goering and Boyce, 1999), strategy-proof optimal tax schemes (Kim and Chang, 1993; Shaffer, 1995), general functional forms for demand (Lee, 1999), the link between pollution taxes and firms' financial decisions (Damania, 2000), asymmetric cost functions among producers (Levin, 1985; Simpson, 1995; Carlsson, 2000), the effects of a shift from specific to *ad valorem* taxation (Okuguchi and Yamazaki, 1994), and the second best environmental taxation with both monopoly and distorting labor taxes (Fullerton and Metcalf, 2002).

the welfare effects of various revenue-neutral tax reforms. The upstream industry produces an intermediate good using labor, and it generates pollution. The downstream industry produces a final good using the intermediate good and labor. I incorporate the above mentioned four distortions into a single framework and introduce four different taxes (or subsidies) for purposes of various tax reforms: a tax on the final good, a tax on the intermediate good, a tax on pollution, and a lump sum transfer to consumers. In my model, both the upstream and downstream producers can substitute one input for another. As I will show later, these extensions are important in that they yield significantly different results from previous studies.

I derive an analytical expression for welfare change from various combinations of tax instruments. Although I show that it is possible to derive a general form of welfare change from various revenue-neutral tax reforms with all these four different tax instruments, I focus on two cases. The first is the case that government uses an *ad valorem* tax on the intermediate good. In many cases, it is difficult to use a tax on pollution due to administrative and technical difficulties (Fullerton, et al, 2001). Therefore, many countries have used various taxes on outputs (or inputs) for the environmental purposes (Barthold, 1994). The second case is when government use a tax on pollution itself, but not a tax on the intermediate good produced by a polluting upstream industry. There might be only a few firms in the two vertically-separated oligopolistic industries. If so, both administration problems and technical difficulties on monitoring might be overcome by government. For these two different cases, I show that the changes in welfare from these tax reforms are functions of the degree of market power as well as input substitutability in both industries, and the demand and cost structures in both industries.

A tax on the intermediate good changes welfare through two separate channels: (i) by changing the final good price and (ii) by changing the intermediate good price. The marginal change in welfare is the sum of the marginal changes in consumer's surplus as well as producers' surplus through these two channels. And it comes from the output effect on welfare from the change in intermediate good production.

My first contribution in this chapter is to identify the third channel that a tax on pollution provides. It causes the upstream producers to substitute between inputs by changing the relative price of labor to pollution. This input substitutability provides the potential strength of a tax on pollution over a tax on the intermediate good, which cannot correctly target the source of the environmental externality when pollution is variable per unit of polluting activities. And this relative superiority of a tax on pollution over a tax on the intermediate good is maintained regardless of whether a lump sum transfer is available. In this chapter, I confirm this point with the case of vertically-separated oligopolies with pollution.

I also examine the directions of various welfare-improving tax reforms in the presence of the market distortions. I derive the condition that determines the direction of a welfare-improving tax reform. In my model, the profit wedges between the unit price and the unit cost in both industries can be interpreted as a simple barometer that shows how serious are the corresponding industry's inefficiencies. With the marginal environmental damages (MED) is included in the model, these marginality conditions for profit decides which tax instruments should be used to improve welfare. Suppose that the distortion from pollution is more serious than the distortions from market imperfection in this economy. Then, the intermediate good production should be discouraged, even if that would aggravate the pre-existing distortions from market imperfection. If a lump sum transfer is feasible and government can only use a tax on the output of the upstream industry—with *no* possibility of a tax on pollution—then it should levy a tax on the intermediate good and use the revenue to give a subsidy to consumers. On the contrary, if the size of environmental damages is smaller than the size of the upstream industry's profit, then it means that the inefficiency problems arising from the upstream industry's market imperfection are more serious than the pollution problem. Then, government should tax consumers and use this revenue to subsidize the upstream industry to increase the production of intermediate good.

In Section 3.2, I present the model and discuss the impact of taxation on the two oligopolistic industries. In Section 3.3, I derive the general welfare expression for various revenue-neutral tax reforms. The welfare effects of the tax reforms when lump sum transfer is available are discussed in Section 3.4. Section 3.5 examines the cases of tax reforms when a tax on the final good is used in revenue-neutral way instead of a lump sum transfer. Section 3.6 is the conclusion.

3.2 THE MODEL

My model is based on those of Colangelo and Galmarini (2001) and Fullerton, et al (2001). My model consists of a representative consumer, the government, and two vertically-separated oligopolistic industries (downstream and upstream). And it is a partial equilibrium model. The upstream industry produces an intermediate good (X) using labor $\left(L^X\right)$ and pollution emissions (E), with a constant returns to scale technology. The downstream industry produces the final consumption good (Y) using the intermediate good (X) and labor $\left(L^Y\right)$, also with a constant returns to scale technology. I assume that the product in each industry is homogeneous and that the numbers of firms in each industry is fixed. Labor is assumed untaxed and competitively supplied.

The representative consumer demands the final consumption good. I assume that the representative consumer's overall utility is separable and linear in both labor and pollution: $U(Y,\ L,\ E) = U(Y) - L - D(E)$, where $L = L^X + L^Y$. The damage function $D(E)$ denotes the disutility to consumer from the aggregate emissions (E). The consumer suffers from E, but she ignores the effect of her own purchases on the aggregate pollution of producers.[46] Then, the inverse demand for Y is:

$$p = p(Y,\quad w), \tag{3.1}$$

where w is the wage rate, p is the consumer price for Y, and $p_Y \equiv \partial p / \partial Y < 0$. In this chapter, I use subscripts to denote the first derivatives as in p_Y except for the indices that denote individual producers, as in x_j and y_i. In contrast, a superscript denotes the industry that a variable represents, as in L^X and L^Y.

3.2.1 Downstream Industry

Each downstream firm i $(i = 1,\ldots,m)$ produces its final good (y_i) using labor and the intermediate good in a constant returns to scale technology.[47] Total industry output is defined as $Y = \sum_{i=1}^{m} y_i$.

[46] This assumption is appropriate if the number of consumers is large. In my model, the consumer represents the choice of many price-taking consumers. This can be interpreted to mean that many consumers lie on a continuum from zero to one, so that the aggregate size of the population is normalized to one.

[47] As in Konishi (1990), I implicitly assume that market inefficiency due to imperfect competition comes from the fixed number of firms and their conjectural behaviors, not from the existence of fixed costs and decreasing average costs.

Each downstream firm maximizes its own profit function:

$$\pi_i^Y = \left[\left(1 - t^Y\right) \cdot p\left(Y,\ w\right) - c^Y\left(q,\ w\right)\right] y_i, \tag{3.2}$$

where q is the price of the intermediate good, t^Y is the *ad valorem* tax rate levied on the consumer price of Y, and $c^Y(q,\ w)$ is the unit cost function. Downstream profit is assumed to be non-negative and untaxed.[48] And the downstream firms take q as fixed in choosing their outputs (and inputs).

I also assume that each downstream firm shares a common conjecture $\left(v^Y\right)$ about how the other firms in its industry will respond to a change in its output level. The conjecture can be defined formally as:

$$v^Y \equiv \frac{dY}{dy_i}, \tag{3.3}$$

where $Y = y_i + \sum_{i' \neq i} y_{i'}$ and $0 \leq v^Y \leq m$. For example, $v^Y = 0$ generates the Bertrand equilibrium with competitive marginal cost pricing, $v^Y = 1$ represents Cournot behavior, and $v^Y = m$ corresponds to perfectly collusive behavior.

Given these conjectures, the first-order necessary condition for the firm's optimizing choice of $y_i > 0$ is that the downstream firm's perceived marginal profit must be equal to zero:[49]

[48] However, a lump sum tax on consumer is equivalent to a profit tax. See Subsection 3.2.4 for the detailed discussion.
[49] Note that this first-order condition is not for any $y_i > 0$, but for optimizing y_i.

$$\left(1-t^{Y}\right)\left(p+\frac{dp}{dY}\frac{dY}{dy_{i}}y_{i}\right)-c^{Y}=0. \tag{3.4}$$

The solution to (3.4) yields an industry with m equal-sized firms. Aggregate all m downstream firms in (3.4) and divide it by $\left(1-t^{Y}\right)$ to get:

$$p\cdot\left(1-\frac{\beta^{Y}}{\varepsilon^{Y}}\right)=\frac{c^{Y}}{1-t^{Y}}, \tag{3.5}$$

where $\varepsilon^{Y}(p,\ w)\equiv -pY_{p}/Y$ is the elasticity of product demand, and $\beta^{Y}\equiv v^{Y}/m\in[0,\ 1]$ is the degree of conjectural variation of the downstream firm, normalized between zero and one. Thus, implicit collusion among firms increases as β^{Y} becomes closer to one. This parameter can be interpreted as the aggregate conjectural variation or the market power parameter.[50] The left-hand side (LHS) of (3.5) is a downstream firm's perceived marginal revenue.

For $y_{i}>0$, I assume that the following existence conditions hold, as in Colangelo and Galmarini (2001):

$$\varepsilon^{Y}>\beta^{Y}, \qquad t^{Y}<1, \qquad \text{and} \qquad c^{Y}<\left(1-t^{Y}\right)\cdot p(0,\ w). \tag{3.6}$$

[50] Therefore, market imperfection comes from the two different sources: first, from the conjectural behaviors of firms $\left(v^{Y}\right)$ and second, from the number of firms (m). I use the normalized aggregate conjectural variation, however, because my paper does not distinguish between these two factors. This normalization is also useful in that β^{Y} can be compared to ε^{Y} in clarifying the existence conditions presented below.

To guarantee the second-order condition, I also assume that the well-known Stern's condition is satisfied (Stern, 1987):

$$G^Y \equiv 1 - \frac{\beta^Y}{\varepsilon^Y}\left(1 - \frac{p\varepsilon_p^Y}{\varepsilon^Y}\right) \; > \; 0, \tag{3.7}$$

where the term $p\varepsilon_p^Y / \varepsilon^Y$ in the bracket is the price elasticity of the elasticity of demand for Y and is always positive.[51] Equation (3.7) is the effect on perceived marginal revenue of a marginal increase in price. Then, the solution function for the final product price is:

$$p = \varphi\left(q, \quad w, \quad t^Y\right). \tag{3.8}$$

In order to see how the inverse demand for Y changes as q and t^Y vary, apply the implicit function theorem to (3.5) and use the stability condition (3.7) to get:

$$p_q \equiv \frac{d\varphi}{dq} = \frac{c_q^Y}{\left(1 - t^Y\right)G^Y} \; > \; 0 \tag{3.9a}$$

and

$$p_{t^Y} \equiv \frac{d\varphi}{dt^Y} = \frac{c^Y}{\left(1 - t^Y\right)^2 G^Y} = \frac{p\left(\varepsilon^Y - \beta^Y\right)}{\varepsilon^Y\left(1 - t^Y\right)G^Y} \; > \; 0. \tag{3.9b}$$

The final good price is raised either by an increase in the price of the intermediate good or by an increase in the *ad valorem* tax on the final good.

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[51] To obtain (3.7), differentiate the LHS of (3.5) with respect to p.

3.2.2 Upstream Industry

Using a constant returns to scale technology, each upstream firm $j \ \ (j = 1,\ldots,n)$ produces intermediate good (x_j) using labor and generates pollution (e_j).[52] Following the conventional approach widely used in the environmental economics literature, I model the aggregate production function for the intermediate good as $X = F(L^X,\ E)$, where $X = \sum_{j=1}^{n} x_j$. Aggregate pollution, $E = \sum_{j=1}^{n} e_j$, has a harmful effect on overall environmental quality and can be disposal of gaseous, liquid, and solid waste used to produce output. This external effect can be captured in the environmental damage function $D(E)$, where the marginal environmental damages (MED) $D_E > 0$. I assume that the government as an environmental regulator can monitor firms' pollution in some cases. I also assume that the enforcement of its environmental policies is effective. Therefore, my paper does not concern administrative, monitoring, or enforcement problems.

Note that the production function for X has variable pollution per unit of output. If the environmental externality is fixed per unit of polluting activities, then the choice of environmental tax instruments becomes trivial since an output tax becomes identical to an emissions tax (Fullerton, et al, 2001).[53] By modeling explicitly the variable relationship between pollution and per unit of output, however, I can show how an output tax affects welfare differently compared to an emissions tax.

An upstream firm acts simultaneously with every other intermediate good producer to maximize the following profit function with respect to its own output x_j:

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[52] Pollution e_j and aggregate pollution E could be measured in tons of emissions such as SO_2, NO_X, or CO_2. Then damages $D(E)$ are measured in units of utility. Emission E could be taxed if each firm's tons of SO_2 or CO_2 can be monitored accurately. For some pollutants, such monitoring is more difficult.

[53] In this case, the output tax rate is equal to the emissions tax adjusted to the proportion of emissions per unit output.

$$\pi_j^X = \left[\left(1 - t^X\right) \cdot q\left(X,\ w,\ t^Y\right) - c^X(r,\ w)\right] x_j, \tag{3.10}$$

where t^X is the *ad valorem* tax rate levied on the price of the intermediate good and $c^X(r,\ w)$ is the unit cost function. The function $q\left(X,\ w,\ t^Y\right)$ is the inverse function of the derived demand for X, which can be derived from the equilibrium aggregate demand for X using the solution function for the final product price.[54]

The unit cost function is a function of the full price of polluting the environment (r), which is the sum of the hidden, internal price of using the environment as an input $\left(r^0\right)$ and a specific tax rate on pollution $\left(t^E\right)$. The polluting firms cannot completely ignore any environmental consequences from their operation, even when there exist neither explicit environmental regulations nor any legal requirements for the environmentally harmful production activities. Firms might simply want to project an environmentally friendly image to the public (Gangadharan, 2001), or voluntary pollution abatement might be used as a barrier to potential entry (Helland and Matsuno, 2003). Environmental regulation tends to change frequently, and anticipating a stricter regulation, firms might prepare themselves by investing pollution abatement equipments (Lee and Alm, 2004).[55] Furthermore, normative and social motivations are as influential as economic motivations in initiating an effort to reduce pollution (Winter and May, 2001; Lai, et al, 2003).[56] Therefore, the term r^0 can be viewed as the price

[54] See (3.15) and (3.16) below for the derivation of the inverse function of the derived demand for the intermediate good.
[55] This kind of motive would be weakened if the grandfathering environmental policies are expected by the polluting firms.
[56] As Earnhart (2004) shows, community characteristics can affect regulatory decisions to intervene against specific facilities with inspections and penalties. If the polluting firms anticipate this, they might be willing to initiate pollution abatement, even in a limited magnitude.

that the upstream producers pay for using the environment without any environmental tax or any explicit environmental regulations.[57] I assume that $r^0 > 0$. Then, t^E serves as one of many possible environmental policy instruments to curtail the discrepancy between r and r^0. I also assume that the relationship between r^0 and t^E is independent from each other for analytical simplicity: $dr^0 / dt^E = 0$ and, therefore, $dr = dt^E$.

Again, I assume that each upstream firm conjectures that a change in its own output alters total industry output by a constant: $v^X \equiv dX / dx_j$, where $0 \leq v^X \leq n$ and $X = x_j + \sum_{j' \neq j}^{n} x_{j'}$.

Define the elasticity of the derived demand for the intermediate good as $\varepsilon^X \left(q,\ w,\ t^Y\right) \equiv -qX_q / X$, define the normalized conjectural variation of the upstream industry as $\beta^X \equiv v^X / n \in [0,\ 1]$, and aggregate the first-order condition from the maximization of (3.10) to obtain:

$$q \cdot \left[1 - \frac{\beta^X}{\varepsilon^X \left(q,\ w,\ t^Y\right)}\right] = \frac{c^X}{1 - t^X}. \tag{3.11}$$

The elasticity of the derived demand for the intermediate good $\left(\varepsilon^X\right)$ can be rewritten as follows:[58]

$$\varepsilon^X = \frac{\sigma^Y w c_w^Y}{c^Y} + \frac{\varepsilon^Y q c_q^Y}{c^Y G^Y}\left(1 - \frac{\beta^Y}{\varepsilon^Y}\right), \tag{3.12}$$

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[57] However, this internal price (r^0) might be sometimes perceived as non-environmental by firms. For example, Joshi, et al (2002) report that firms' accounting systems tend to classify incorrectly the substantial amount of costs incurred due to environmental reasons, and they are often unaware of existence and magnitude of these costs.

[58] See Appendix B.1 for derivation of (3.12).

where σ^Y denotes the input substitution elasticity between L^Y and X in production of Y.

The upstream industry's existence and stability conditions are analogous to those of the downstream industry, namely:

$$\varepsilon^X > \beta^X, \quad t^X < 1, \quad t^E < 1, \quad \text{and} \quad w < \left(1 - t^X\right) \cdot q\left(0,\ w,\ t^Y\right), \tag{3.13}$$

and

$$G^X \equiv 1 - \frac{\beta^X}{\varepsilon^X}\left(1 - \frac{q\varepsilon_q^X}{\varepsilon^X}\right) > 0, \tag{3.14}$$

where the term $q\varepsilon_q^X / \varepsilon^X$ in the bracket is the price elasticity of the elasticity of the derived demand for X and is always positive.[59]

By Shepard's lemma, the equilibrium aggregate demand for X is given by:

$$X = c_q^Y(q,\ w) \cdot Y(p,\ w).$$

Rewrite it, using (3.8), to obtain:

$$X = c_q^Y(q,\ w) \cdot Y\left(\varphi\left(q,\ w,\ t^Y\right),\ w\right) = X\left(q,\ w,\ t^Y\right). \tag{3.15}$$

Define $c_{qq}^Y \equiv \partial^2 c^Y / (\partial q)^2$. Then, since $X_q \equiv \partial X / \partial q = c_{qq}^Y Y + c_q^Y Y_p \varphi_q$ is negative and finite as long as c_{qq}^Y is negative and finite, I can invert (3.9) to obtain the derived demand function:[60]

[59] To obtain (3.14), differentiate the LHS of (3.11) with respect to q.

$$q = q\left(X,\ w,\ t^{Y}\right), \tag{3.16}$$

where $q_X < 0$ and $q_{t^Y} < 0$.[61]

From (3.11), the equilibrium price function for the intermediate good can be rewritten by using the corresponding existence and stability conditions (since $r = r^0 + t^E$):

$$q = \xi\left(r,\ w,\ t^{X},\ t^{Y}\right) = \xi\left(r^{0},\ w,\ t^{X},\ t^{Y},\ t^{E}\right). \tag{3.17}$$

Note that q is endogenous, because the upstream sector is explicitly analyzed in my model.

Substitute (3.17) into (3.8) to obtain:

$$\begin{aligned} p &= \varphi\left(\xi\left(r,\ w,\ t^{X},\ t^{Y}\right),\ w,\ t^{Y}\right) \\ &= \varphi\left(r,\ w,\ t^{X},\ t^{Y}\right) \\ &= \varphi\left(r^{0},\ w,\ t^{X},\ t^{Y},\ t^{E}\right). \end{aligned} \tag{3.18}$$

To see how taxes affect prices, totally differentiate (3.11) and use the definition of G^X in (3.14) to get:

$$G^{X}\ dq + \frac{\beta^{X} q \varepsilon_{t^{Y}}^{X}}{\left(\varepsilon^{X}\right)^{2}}\ dt^{Y} = \frac{c^{X}}{\left(1-t^{X}\right)^{2}}\ dt^{X} + \frac{c_{r}^{X}}{1-t^{X}}\ dt^{E}, \tag{3.19}$$

60 If inputs are not perfect substitutes for each other, then $c_q^Y Y_p \varphi_q$ is negative and finite.

where $\varepsilon_{t^Y}^X \equiv \partial\varepsilon^X / \partial t^Y$. The partial derivatives of (3.17) with respect to t^X, t^Y, and t^E are obtained by setting the corresponding terms equal to zero as follows:[62]

$$\frac{dq}{dt^X} \equiv \xi_{t^X} = \frac{\left(\varepsilon^X - \beta^X\right)q}{\varepsilon^X\left(1-t^X\right)G^X} > 0, \tag{3.20a}$$

$$\frac{dq}{dt^Y} \equiv \xi_{t^Y} = -\frac{\beta^X q \varepsilon_{t^Y}^X}{\left(\varepsilon^X\right)^2 G^X}, \tag{3.20b}$$

and

$$\frac{dq}{dt^E} \equiv \xi_{t^E} = \frac{c_r^X}{\left(1-t^X\right)G^X} > 0. \tag{3.20c}$$

Equations (3.20a) and (3.20c) show that either a tax on upstream producers' output $\left(t^X\right)$ or a tax on their pollution $\left(t^E\right)$ increase the intermediate good price (q), since both increase the intermediate good's marginal cost of production. However, the sign of (3.20b) is ambiguous. If the upstream industry applies competitive marginal cost pricing $\left(\beta^X = 0\right)$, then the change in downstream tax t^Y has no effect on the price of upstream intermediate good. On the other hand, if the upstream industry has some degree of market power $\left(\beta^X > 0\right)$, then the sign of (3.20b) critically depends on the sign of $\varepsilon_{t^Y}^X$, which denotes how the downstream taxation changes the elasticity of the derived demand for X. In particular, if $\varepsilon_{t^Y}^X > 0$, that is, ε^X becomes more elastic as t^Y is raised, then t^Y would decrease q. For example, if the curvature of

61 See (3.20b) below and the subsequent discussion about the sign of q_{t^Y}.

62 Recall that $dr = dt^E$ since I assumed that $r^0 > 0$ but $dr^0 = 0$.

demand function for Y is concave or weakly convex (i.e., linear or exponential), then $\varepsilon_{t^Y}^X > 0$, and an increase in t^Y would decrease q.[63]

To see the effects of tax rates on the final good price, differentiate (3.18) with respect to the corresponding taxes:

$$\frac{dp}{dt^X} \equiv \varphi_q \cdot \xi_{t^X} = \frac{c_q^Y}{\left(1-t^Y\right)G^Y}\frac{\partial q}{\partial t^X} \; > \; 0, \tag{3.21a}$$

$$\begin{aligned} \frac{dp}{dt^Y} &\equiv \varphi_{t^Y} + \varphi_q \cdot \xi_{t^Y} \\ &= \frac{\left(\varepsilon^Y - \beta^Y\right)p}{\varepsilon^Y \cdot \left(1-t^Y\right)G^Y} + \frac{c_q^Y}{\left(1-t^Y\right)G^Y}\frac{\partial q}{\partial t^Y}, \end{aligned} \tag{3.21b}$$

and
$$\frac{dp}{dt^E} \equiv \varphi_q \cdot \xi_{t^E} = \frac{c_q^Y}{\left(1-t^Y\right)G^Y}\frac{\partial q}{\partial t^E} \; > \; 0. \tag{3.21c}$$

Equations (3.21a) and (3.21c) show that both upstream t^X and t^E increase final output price p. However, the sign of (3.21b) is ambiguous. Unlike t^X and t^E, a tax on the final good $\left(t^Y\right)$ has two channels through which it affects p. The first term in the right hand side (RHS) of (3.21b) denotes the direct effect that makes p increase with t^Y, while the second term denotes the indirect effect that works through the change in q. The sign of this indirect effect is determined by the sign of $\varepsilon_{t^Y}^X$ as already shown in (3.20b). Therefore, the final sign of (3.21b) is determined by the relative size of the direct and indirect effects. A sufficient condition for (3.21b) to be positive is that $\varepsilon_{t^Y}^X \le 0$. Even if $\varepsilon_{t_Y}^X > 0$, however, as is the case for most product demand specifications, it would be difficult to find a case where the indirect effect

[63] However, if $\varepsilon_{t^Y}^X = 0$ (i.e., isoelastic demand), then t^Y would have no effect on q even if $\beta^X > 0$.

outweighs the direct effect such that the final sign of (3.21b) is negative (Colangelo and Galmarini, 2001).

3.3 WELFARE CHANGES FROM TAX REFORMS

In this subsection, I derive the general welfare expression that will be used for various tax reforms in the following sections. The economy is assumed to have no revenue requirement, so taxes are used merely to lessen the distortions caused by imperfect competition as well as by the externality. This chapter does not examine the problems of optimal taxation. Solving an optimal taxation problem is more difficult than solving a tax reform problem. It is possible to obtain analytical solution for optimal taxes only in very restrictive cases. Since the main interest of my paper is about how the government can improve welfare by introducing a revenue-neutral tax-subsidy reform in the presence of vertically-separated oligopolies, I focus on tax system rather than optimal taxation.

I start from an arbitrary tax system, where rates are not necessarily set optimally. Then, I solve for the effects on welfare of a proposed tax reform that is, an increase in one tax rate with a revenue-neutral decrease in some other tax rate. First, I examine what factors determine the direction of welfare change from that particular tax reform. Then, if the effect on welfare is positive, which is interpreted as a good tax reform, I examine the factors that determine the magnitude of welfare change.[64]

[64] It is uncertain whether that is the best possible small tax reform, however, because there might be a larger increase in welfare by raising some other tax rate and/or lowering some other tax rate. If my result happened to be at the optimum, then any small revenue-neutral change in tax rates will yield *no* change in welfare.

Given the assumptions on consumer preferences and other agents in this economy, social welfare is defined as the unweighted sum of consumers' and producers' surplus as follows:

$$W = W\left(t^X,\ t^Y,\ t^E,\ T\right) = CS + \frac{\Pi^X + \Pi^Y + T}{w} \tag{3.22}$$

where consumer surplus is defined as $CS \equiv U\left(Y\left(p,\ w\right)\right) - p \cdot Y\left(p,\ w\right)/w - D\left(E\right)$. The producers' surplus $\left(PS\right)$ consists of the upstream and downstream industries' profit functions: $\Pi^X = \left[\left(1 - t^X\right) \cdot q\left(X,\ w,\ t^Y\right) - c^X\left(r,\ w\right)\right] X$ and $\Pi^Y = \left[\left(1 - t^Y\right) \cdot p\left(Y,\ w\right) - c^Y\left(q,\ w\right)\right] Y$, respectively. The government tax revenue is given as:[65]

$$T = t^X q X + t^Y p Y + t^E E = \left[t^Y p + c_q^Y\left(t^X q + t^E c_r^X\right)\right] Y. \tag{3.23}$$

Totally differentiate (3.23), assuming no pre-existing taxes $\left(t^X = t^Y = t^E = T = 0\right)$, to get:

$$dT = \left(q c_q^Y\, dt^X + p\, dt^Y + c_r^X c_q^Y\, dt^E\right) Y. \tag{3.24}$$

This is the change in the lump sum transfer necessary for government to balance the budget when introducing other new taxes. Totally differentiate (3.22), substitute (3.24) into it, and use $dW/dT = 1/w$ from (3.22) to get:

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65 By Shepard's lemma, $X = c_q^Y Y$ and $E = c_r^X X = c_r^X c_q^Y Y$.

$$dW = \left(\frac{\partial W}{\partial t^X} + \frac{qX}{w} \right) dt^X + \left(\frac{\partial W}{\partial t^Y} + \frac{pY}{w} \right) dt^Y + \left(\frac{\partial W}{\partial t^E} + \frac{E}{w} \right) dt^E . \tag{3.25}$$

Rewrite (3.25) as:[66]

$$\begin{aligned} dW = & -\left[\frac{\varepsilon^Y \left(\Pi^X + \Pi^Y - wD_E E \right)}{wp} \frac{dp}{dt^X} + \frac{\sigma^Y c_w^Y \left(\Pi^X - wD_E E \right)}{qc^Y} \frac{dq}{dt^X} \right] dt^X \\ & -\left[\frac{\varepsilon^Y \left(\Pi^X + \Pi^Y - wD_E E \right)}{wp} \frac{dp}{dt^Y} + \frac{\sigma^Y c_w^Y \left(\Pi^X - wD_E E \right)}{qc^Y} \frac{dq}{dt^Y} \right] dt^Y \\ & -\left[\begin{array}{c} \dfrac{\varepsilon^Y \left(\Pi^X + \Pi^Y - wD_E E \right)}{wp} \dfrac{dp}{dt^E} + \dfrac{\sigma^Y c_w^Y \left(\Pi^X - wD_E E \right)}{qc^Y} \dfrac{dq}{dt^E} \\ -\dfrac{\sigma^X c_w^X wD_E E}{r^0 c^X} \end{array} \right] dt^E . \end{aligned} \tag{3.26}$$

Equation (3.26) shows how the government can improve welfare by initiating a revenue-neutral tax reform when a lump sum transfer is available. The government can use any (or all) of three possible tax instruments: a tax on pollution $\left(t^E\right)$, and two taxes on outputs (t^X and t^Y). All tax reforms have in common two separate channels through which change welfare. The first term containing ε^Y in each large bracket denotes how the introduction of a small t^X (or t^Y or t^E) and the corresponding change in T affect welfare through p. This marginal change

66 See Appendix B.2 for derivation of (3.26).

in welfare is the sum of the marginal changes in CS and PS, which is closely related to the change in consumer demand for Y due to the change in p (i.e., ε^Y). Therefore, this is the "output effect" on welfare from the change in Y.[67]

On the other hand, the second term containing σ^Y in each large bracket denotes how the introduction of a small t^X (or t^Y or t^E) and the matching change in T alter welfare through q. Again, this marginal change in welfare is the sum of the marginal changes in CS and PS, which is closely related to the change in cost of Y and the downstream firms' technological ability to accommodate the effects of a tax on cost by substituting L^Y for X (i.e., σ^Y). Therefore, this is the output effect on welfare from the change in X. (Or, this could be called a substitution effect in Y, since output of X is an input to Y.)

In addition to these two common channels, the combination of t^E and T (i.e., dW/dt^E) has another way to change welfare: the third, last term in the large bracket containing σ^X. This change comes not from the changes of either p or q, but from the marginal change in cost of X. A specific tax on pollution directly affects the upstream producers' cost by changing the relative input price. This is the "substitution effect" on welfare from the change in E.

Market imperfection usually prescribes a subsidy for (rather than a tax on) the market output because a tax would decrease the already suboptimal level of production due to market imperfection. On the other hand, the presence of environmental

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[67] The reason that $D_E E$ is multiplied by w is as follows. The utility function is defined as $U = U(Y) - L - D(E)$, which essentially means that utility is measured in labor hours $\left(\partial U / \partial L = -1\right)$. If utility is measured in labor hours, then multiplication by w yields dollars. Since D_E is in utils $\left(\partial U / \partial E\right)$, multiply by w to get hours. Equivalently in (3.26), divide $\left(\Pi^X + \Pi^Y\right)$ by w to get utils for dW/dt^E (which is measured in utils).

externality prescribes policy makers to levy a tax.[68] Simultaneous presence of market imperfection and environmental externality, however, could offer policy makers conflicting recommendations, especially when taxes or subsidies are employed for their corrective roles in lessening inefficiencies.

While many studies of the optimal taxation provide relatively clear rules and answers on the effects of tax policies in various market conditions, it is difficult to find actual taxes based on these principles. Many taxes are not correctly targeted to the sources of inefficiencies, due to administrative and technological difficulties, and few environmental taxes are believed to set optimally (OECD, 1995 and 1999b; Fullerton, et al, 2001). Political considerations or the practical problems of design and implementation such as who is to be taxed are often the most important factors that determine the types of policy tools employed (Barthold, 1994). Therefore, it is important to know welfare-improving directions of a tax reform and what factors decide it before the government initiates a tax reform. And this might be an important starting point to implement a full-fledged optimal tax policy, especially in the case of vertically-separated oligopolies with pollution, where various distortions are interlinked.

The above welfare expression (3.26) does exactly that. It provides the conditions that decide the direction of a welfare-improving tax reform. However, (3.26) is expressed in 'total' terms containing industry profits (Π^X and Π^Y), which make it difficult interpret. So I reaarange (3.26), using (B2.6), to obtain:

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[68] This tax would apply to output if pollution is fixed per unit of output. More generally, as here, it is a tax per unit of pollution created by production or consumption activities, set equal to the marginal environmental damage (MED) (Pigou, 1932; Baumol and Oates, 1988).

$$wW_p = wU_Y Y_p - Y - pY_p - wD_E c_r^X c_q^Y Y_p$$

$$+\left[\left(1-t^Y\right)p - c^Y\right]Y_p + \left(1-t^Y\right)Y + \left[\left(1-t^X\right)q - c^X\right]c_q^Y Y_p.$$

Set $t^X = t^Y = 0$, then:

$$wW_p\Big|_{t^X=t^Y=0} = -wD_E c_r^X c_q^Y Y \frac{pY_p}{Y}\frac{1}{p_p} + \left(q - c^X\right)c_q^Y Y \frac{pY_p}{Y}\frac{1}{p} + \left(p - c^Y\right)Y \frac{pY_p}{Y}\frac{1}{p}$$

$$= -\frac{\varepsilon^Y Y}{p}\left[\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right)\right].$$

Therefore,

$$W_p\Big|_{t^X=t^Y=0} = -\frac{\varepsilon^Y Y}{wp}\left[\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right)\right]. \tag{3.26a}$$

The term $\left(q - c^X\right)$ represents the upstream industry's profit wedge, which is the difference between the product price (q) and the unit (marginal) cost $\left(c^X\right)$. Note that $\left(q - c^X\right) \geq 0$ since $q\left(1 - \beta^X/\varepsilon^X\right) = c^X$, $\beta^X < \varepsilon^X$, and $\beta^X \in [0,\ 1]$. Similarly, $\left(p - c^Y\right) \geq 0$ represents the downstream industry's profit wedge. Another term $wD_E c_r^X$ in (3.26a) is the MED from the pollution emitted by the upstream industry. Note that there is no term for the MED in the downstream industry's profit wedge, since the downstream industry does not emit pollution.

Similarly,

$$W_q\big|_{t^X=t^Y=0} = -\frac{\sigma^Y c_w^Y X}{q c^Y}\left(q - c^X - wD_E c_r^X\right). \tag{3.26b}$$

3.4 WELFARE IMPROVING TAX POLICIES WITH A LUMP SUM TRANSFER TO CONSUMER

3.4.1 Welfare Improving Tax Policies with a Lump Sum Transfer to Consumer

Suppose that government uses a tax on the intermediate good $\left(t^X\right)$ and a lump sum transfer to consumer (T). Set $dt^Y = dt^E = 0$ in (3.26) and use (3.20a), (3.21a), (3.26a), and (3.26b) to obtain:

$$\frac{dW}{dt^X} = W_p \frac{dp}{dt^X} + W_q \frac{dq}{dt^X}$$

$$= -\frac{\varepsilon^Y q c_q^Y Y\left[\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right)\right]}{wpG^Y}\frac{1}{G^X}\left(1 - \frac{\beta^X}{\varepsilon^X}\right) \tag{3.27}$$

$$-\frac{\sigma^Y c_w^Y X\left(q - c^X - wD_E c_r^X\right)}{c^Y}\frac{1}{G^X}\left(1 - \frac{\beta^X}{\varepsilon^X}\right).$$

With no environmental damages $\left(D_E = 0\right)$, the above (3.27) is always non-positive, which means that the government can improve welfare by using $t^X < 0$ (and $T > 0$). This extends the results from previous environmental studies to the case of two vertically-separated industries: the marginalization distortion can be lessened by a subsidy (Buchanan, 1969; Barnett, 1980).

The above result shows that there are two separate channels through which the government can improve welfare by using t^X and T: (i) through affecting the price of final good $\left(W_p dp/dt^X\right)$ and (ii) through affecting the price of intermediate good $\left(W_q dq/dt^X\right)$. The above result also shows that the magnitude of welfare change depends on several important industry parameters: the elasticities of demand (ε^X and ε^Y), the market powers in both industries (β^X and β^Y), the cost structure of the downstream industry (c_q^Y and c_w^Y), the input substitutability of the downstream firms $\left(\sigma^Y\right)$, the both industries' profit wedges along with the MED included: $\left(q - c^X - wD_E c_r^X\right) c_q^Y + \left(p - c^Y\right)$.

Recall that from (3.26), the marginal change in welfare comes from the two separate "marginal" changes. The first source of the welfare change is $W_p dp/dt^X$. This consists of various parameters such as the elasticity of demand $\left(\varepsilon^Y\right)$ and the marginal cost of the downstream industry $\left(c_q^Y\right)$. Multiplied by these "marginal" parameters, the first term in (3.26), as a whole, represents the "marginal" change in welfare by the introduction of a small tax on the intermediate good $\left(t^X\right)$ through affecting the price of final good. The same logic is applied to the second term in (3.26).

Keeping this point in mind, the expression (3.27) provides an interesting condition that decides the direction of the tax reform: $\left(q - c^X - wD_E c_r^X\right) c_q^Y + \left(p - c^Y\right)$. These terms can be interpreted as how serious the corresponding distortion is to social welfare. In my model, the upstream industry is the source of three inefficiencies: the environmental damages, the marginalization distortion, and the downstream industry's input-mix distortion caused by this marginalization distortion. Therefore, the upstream industry's profit wedge along with the MED included can be interpreted as a signal to the government that shows how serious are the distortions from market imperfection in the upstream industry as well as from pollution. Similarly, the downstream industry's profit wedge represents how serious the distortion from the downstream market imperfection is.

If the wedges from the distortions in both industries are negative, that is, if $\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right) < 0$, which makes the sign of (3.27) positive, then intermediate good production should be discouraged in this second-best world with no t^E, even if doing so would aggravate the distortions from market imperfection. And the policy recommendation should be a tax on the intermediate good $\left(t^X > 0\right)$.

On the contrary, if $\left(q - c^X - wD_E c_r^X\right)c_q^Y > 0$, which makes the sign of (3.27) negative, then a welfare-improving, revenue-neutral tax reform consists of a subsidy for the upstream industry $\left(t^X < 0\right)$ and a lump sum tax on consumers $(T > 0)$. The subsidy for X makes production increase and price fall in the upstream industry. The decrease in price reduces profits, but it raises consumer surplus. At the same time, the lump sum tax on consumers reduces consumer income, while the subsidy increases profits. The final effect would be the increase in both profits and welfare.

However, if $\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right) > 0$ but $\left(q - c^X - wD_E c_r^X\right) < 0$, then the final sign of (3.27) becomes ambiguous. The input substitutability of the downstream industry $\left(\sigma^Y\right)$ emerges as an important factor in this case. If the downstream firms can freely substitute inputs X and L^Y, the upstream industry's market power substantially weakens. Then, a tax on X would greatly improve welfare by reducing environmental damages, while it would not so much aggravate the distortions from the upstream industry's imperfect competition. If

σ^Y is sufficiently high, then the sign of the whole welfare expression (3.27) becomes positive. In that case, government can improve welfare by taxing intermediate good.

Would a subsidy for the intermediate good $\left(t^X < 0\right)$ generate more pollution due to the decrease in price (q) and the resulting increase in demand by the downstream industry? Should the government reduce the subsidy level if it takes into account the possible additional environmental damages that might result from the subsidy? The answer is no. Consider the nature of the lump sum transfer to consumers in this case. With the initial condition of no pre-existing taxes, a subsidy for X results in more X, more E, lower q, and more Y. Revenue from consumers exactly compensates these effects because a lump sum tax on consumers is not really a different instrument but a compensated income for the subsidy for X.

3.4.2 A Tax on Pollution with a Lump Sum Transfer to Consumer

The case of using only a tax on pollution $\left(t^E\right)$ can be obtained by setting $dt^X = dt^Y = 0$ in (3.26):

$$\frac{dW}{dt^E} = -\frac{\varepsilon^Y c_r^X c_q^Y Y\left[\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right)\right]}{wpG^X G^Y} - \frac{\sigma^Y c_r^X c_w^Y X\left(q - c^X - wD_E c_r^X\right)}{qc^Y G^X} + \frac{\sigma^X c_w^X wD_E E}{r^0 c^X}. \tag{3.28}$$

Note that the first two terms in (3.28) are similar to those in (3.27). If the government introduces a tax on pollution $\left(t^E > 0\right)$, then the price of the intermediate good (q) increases, which in turn raises the production cost of Y as well as p. This causes the product demand for Y to decrease. Then, the downstream industry's derived demand for X falls. The first term containing ε^Y in (3.28) shows this output effect of t^E through the downstream industry. On the other hand, the increase in q makes the downstream firms substitute from X into L^Y, which has now become relatively cheaper due to the introduction of t^E. This output effect on X due to the input substitution by the downstream industry is captured in the second term containing σ^Y in (3.28). Note that these two effects are also present in (3.27) and come about from a single source: the decrease in production of X.

Ignoring the last σ^Y term for the time being, the signs of the first two terms in (3.28) depends on the signs of the profit wedge, as already explained in (3.27). For example, if $\left(q - c^X - wD_E c_r^X\right) + \left(p - c^Y\right) < 0$, then the sign of (3.28) becomes positive. And government can improve welfare by using $t^E > 0$ and $T < 0$. On the other hand, if $\left(q - c^X - wD_E c_r^X\right) > 0$, then the signs of the first two terms in (3.28) are both negative. It means that if the government has only t^E at its disposal (t^X must be zero), then government should introduce $t^E < 0$ and $T > 0$ to improve welfare. This particular policy recommendation appears against common sense because the polluting activity is being subsidized rather than penalized. However, it is perfectly understandable if considered in the context of social welfare. If $\left(q - c^X - wD_E c_r^X\right) > 0$, it means that the price wedge in the upstream industry is big even considering the MED. Hence, the distortions from the upstream industry's imperfect competition are most pressing. Therefore, the production of X should be encouraged, even if the only way to do that is a subsidy for E. By doing so, the price of X would fall and the downstream firms' derived demand for X would increase. As a result, the double marginalization as well as the input-mix distortions lessens.

However, note that the last term that has σ^Y in (3.28) is always positive, which denotes the input substitution effect of t^E. This effect comes from the fact that a tax on pollution correctly targets the source of distortion (Fullerton, et al, 2001). Equation (3.28) shows that this superiority of t^E to t^X is also valid in the case of vertically-separated oligopolies with pollution. To see this point more clearly, assume Bertrand competition in both industries. Set $G^X = G^Y = 1$, $p = c^Y$, $q = c^X$ and $\beta^X = \beta^Y = 0$ in both (3.27) and (3.28) to get:

$$\frac{dW}{dt^X} = \frac{\varepsilon^Y q c_q^Y w D_E E}{wp} + \frac{\sigma^Y c_w^Y w D_E E}{c^Y} > 0 \tag{3.29a}$$

and

$$\frac{dW}{dt^E} = \frac{\varepsilon^Y c_r^X c_q^Y w D_E E}{wp} + \frac{\sigma^Y c_r^X c_w^Y w D_E E}{qc^Y} + \frac{\sigma^X c_w^X w D_E E}{r^0 c^X} > 0\,. \tag{3.29b}$$

With no distortions from imperfect competition in either industry, there remains only one inefficiency in my model: the distortion from pollution (D_E). In this case, the government can always improve welfare by introducing either t^X or t^E incrementally as shown in (3.29a) and (3.29b), respectively. The first two terms in both expressions reflect the welfare gain from the output effect due to decrease in X. However, (3.29b) has the third, positive term, which is the input substitution effect between E and L^X in the upstream industry.

3.5 TAX POLICIES WITH NO LUMP SUM TRANSFER

Now, I examine the cases that a lump sum transfer is not feasible nor any other tax to raise revenue that can be used to pay for subsidies or to rebate revenue. Again, I start at an initial equilibrium with no pre-existing taxes. Government uses a tax on (or a subsidy for) Y to balance the budget when it introduces a new tax on (or a subsidy for) the upstream industry (t^X or t^E). In this case, two different combinations of tax reforms are available to the government: $\left(t^X,\ t^Y\right)$ and $\left(t^E,\ t^Y\right)$.[69]

Set $dT = 0$ in (3.25), assuming no pre-existing taxes, to get:

$$dt^Y = -\left(\frac{qX}{pY}\right)dt^X - \left(\frac{E}{pY}\right)dt^E. \tag{3.30}$$

This is the change in t^Y necessary for government to balance the budget when introducing either t^X or t^E.

Totally differentiate the social welfare function (3.22) and use (3.30) to get: [70]

$$\begin{aligned} dW = &\left[W_p\left(\frac{dp}{dt^X} - \frac{dp}{dt^Y}\frac{qX}{pY}\right) + W_q\left(\frac{dq}{dt^X} - \frac{dq}{dt^Y}\frac{qX}{pY}\right)\right]dt^X \\ &+ \left[\begin{array}{c} W_p\left(\dfrac{dp}{dt^E} - \dfrac{dp}{dt^Y}\dfrac{E}{pY}\right) \\ +W_q\left(\dfrac{dq}{dt^E} - \dfrac{dq}{dt^Y}\dfrac{E}{pY}\right) + \dfrac{\sigma^X c_w^X w D_E E}{r^0 c^X} \end{array}\right]dt^E. \end{aligned} \tag{3.31}$$

69 I do not consider the case of $\left(t^X,\ t^E\right)$, for reasons explained above.

70 See Appendix B.3 for derivation of (3.31).

Equation (3.31) shows how the government can improve welfare by using various tax reforms when a lump sum transfer is infeasible.

3.5.1 Ad Valorem Taxes on Both Goods

In this section, I consider the case that the government can only use output taxation for both industries: t^Y and t^X. Set $dt^E = 0$ in (3.31) to get:

$$\frac{dW}{dt^X} = W_p\left(\frac{dp}{dt^X} - \frac{dp}{dt^Y}\frac{qX}{pY}\right) + W_q\left(\frac{dq}{dt^X} - \frac{dq}{dt^Y}\frac{qX}{pY}\right). \tag{3.32}$$

When a lump sum transfer is available, only t^X affects prices dp/dt^X and dq/dt^X as shown earlier in (3.27), since a lump sum transfer does not change the relative price. However, when a lump sum transfer is not available, not only t^X but also t^Y affects both p and q. Moreover, unlike a lump sum transfer, t^Y changes the prices in more complicated ways. While t^Y changes q directly, it affects p in two ways: the direct effect on the final good price $\left(\partial p/\partial t^Y\right)$ and the indirect one through the intermediate price $\left(\partial p/\partial q\right)\left(dq/dt^Y\right)$.

Substitute (3.20a), (3.20b), (3.21a), (3.21b), (3.26a), (3.26b), (B2.6) and (B2.7) into (3.32) to obtain:

$$\frac{dW}{dt^X} = -\frac{\varepsilon^Y qc_q^Y Y\left[\left(q - c^X - wD_E c_r^X\right)c_q^Y + \left(p - c^Y\right)\right]}{wpG^Y}\left[\begin{array}{c}\frac{1}{G^X}\left(1-\frac{\beta^X}{\varepsilon^X}\right)-\left(1-\frac{\beta^Y}{\varepsilon^Y}\right)\\ +\frac{\beta^X qc_q^Y \varepsilon_{t^Y}^X}{\left(\varepsilon^X\right)^2 pG^X}\end{array}\right]$$

$$-\frac{\sigma^Y c_w^Y X\left(q - c^X - wD_E c_r^X\right)}{qc^Y}\left[\frac{1}{G^X}\left(1-\frac{\beta^X}{\varepsilon^X}\right)+\frac{\beta^X qc_q^Y \varepsilon_{t^Y}^X}{\left(\varepsilon^X\right)^2 pG^X}\right]. \tag{3.33}$$

The first component in the large brackets $\frac{1}{G^X}\left(1-\frac{\beta^X}{\varepsilon^X}\right)$ measures the upstream industry's degree of market power. The second term in the large bracket $\left(1-\frac{\beta^Y}{\varepsilon^Y}\right)$ reflects the downstream industry's degree of market power. And the third term $\beta^X q\varepsilon_{t^Y}^X \Big/ \left(\varepsilon^X\right)^2 pG^X$ represents the effect of downstream taxation on the price of the final good through the change of the price of intermediate good. Combining these terms, the first line of (3.33) represents the welfare effect generated by the change in the product demand for Y, while the second line captures the welfare effect resulting from the change in the derived demand for X.

Using the definitions of G^X from (3.14), the first term in the large brackets can be rewritten as follows:

$$\frac{1}{G^X}\left(1-\frac{\beta^X}{\varepsilon^X}\right) = \frac{\left(\varepsilon^X - \beta^X\right)}{\left(\varepsilon^X - \beta^X\right) + \frac{\beta^X q\varepsilon_q^X}{\varepsilon^X}}. \tag{3.34}$$

If the elasticity of the derived demand for X by the downstream industry is not increasing in q, that is, if $\varepsilon_q^X \le 0$, then (3.34) is greater than or equal to one.[71] The second component of the large bracket in the first line of (3.33), $\left[1-\left(\beta^{Y}/\varepsilon^{Y}\right)\right]$, is always less than one because it is already assumed that $\varepsilon^{Y} > \beta^{Y}$ in (3.6). Therefore, the difference between these two components is positive. Furthermore, if the elasticity of the derived demand for X is not decreasing in t^{Y}, that is, if $\varepsilon_{t^{Y}}^{X} \geq 0$, which is a reasonable assumption for most demand profiles, the third component of the large bracket in the first line of (3.33) is also positive. Hence, the sign of the large bracket in the first line of (3.33) is positive. In the same fashion, it can be shown that the sign of the large bracket in the second line of (3.33) is also positive. Therefore, the overall sign of (3.33) again depends only on the industry profit conditions.

The above two conditions that $\varepsilon_{q}^{X} \leq 0$ and $\varepsilon_{t^{Y}}^{X} \geq 0$ ensure that the corresponding tax/subsidy scheme will be more effective, by strengthening or weakening the upstream industry's market power in a certain direction. For example, if $\left(q - c^{X} - wD_{E}c_{r}^{X}\right) > 0$, which denotes the situation where the market imperfection problem in the upstream industry is more damaging to welfare than the environmental problem, then the government could improve welfare using $t^{X} < 0$ and $t^{Y} > 0$. A subsidy for X reduces q. However, the first condition $\varepsilon_{q}^{X} \leq 0$ keeps the downstream producers' elasticity of the derived demand for X from becoming less elastic due to this decrease in q, which means that the upstream industry's market power weakens. On the other hand, a tax on Y raises q, but the second condition $\varepsilon_{t^{Y}}^{X} \geq 0$ ensures that this tax on Y does not increase q further through changing ε^{X}, which keeps the upstream firms' market power weak.

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71 Both $G^{X} > 0$ and $\left[1-\left(\beta^{X}/\varepsilon^{X}\right)\right] > 0$. Hence, $\left[1-\left(\beta^{X}/\varepsilon^{X}\right)\right]/G^{X} > 0$.

However, if $\left(p-c^{Y}\right)+\left(q-c^{X}-wD_{E}c_{r}^{X}\right)c_{q}^{Y}<0$, which means that the environmental problem is more severe than the market imperfection problem in both industries, then a tax reform should be reversed to $t^{X}>0$ and $t^{Y}<0$. First, $t^{X}>0$ increases q, but $\varepsilon_{q}^{X}\leq 0$ means that this increase in q does not make ε^{X} more elastic. Second, $\varepsilon_{t^{Y}}^{X}\geq 0$ ensures that $t^{Y}<0$ does not decrease q. Therefore, the upstream market power is at least maintained same or strengthened. However, government levies $t^{X}>0$ and tolerates the higher q, since the higher q means the less X and consequently, the smaller $wD_{E}E$, which lessens the more pressing pollution problem. Again, this is all where t^{E} is not available, and where the revenue effect of a change in t^{Y} must offset the revenue effect of a change in t^{X}.

3.5.2 Emissions Tax

In this section, I consider the case where government uses the combination of t^{E} and t^{Y}. Set $dt^{X}=0$ in (3.31) and use (B2.6), (B2.7), (3.20b), (3.20c), (3.21b), (3.21c), (3.26a), and (3.26b) to get:

$$\begin{aligned}\frac{dW}{dt^{E}}=&-\frac{\varepsilon^{Y}c_{r}^{X}c_{q}^{Y}Y}{wpG^{Y}}\begin{bmatrix}\left(q-c^{X}-wD_{E}c_{r}^{X}\right)c_{q}^{Y}\\+\left(p-c^{Y}\right)\end{bmatrix}\left[\frac{1}{G^{X}}-\left(1-\frac{\beta^{Y}}{\varepsilon^{Y}}\right)+\frac{\beta^{X}qc_{q}^{Y}\varepsilon_{t^{Y}}^{X}}{\left(\varepsilon^{X}\right)^{2}pG^{X}}\right]\\&-\frac{\sigma^{Y}c_{w}^{Y}c_{r}^{X}X}{qc^{Y}}\left(q-c^{X}-wD_{E}c_{r}^{X}\right)\left[\frac{1}{G^{X}}+\frac{\beta^{X}qc_{q}^{Y}\varepsilon_{t^{Y}}^{X}}{\left(\varepsilon^{X}\right)^{2}pG^{X}}\right]+\frac{\sigma^{X}c_{w}^{X}wD_{E}E}{r^{0}c^{X}}.\end{aligned} \tag{3.40}$$

As t^E is levied on the upstream industry, the input substitutability of the upstream industry $\left(\sigma^X\right)$ appears in the welfare expression in addition to other factors affecting the magnitude of welfare change. Note that the sign of (3.40) is now determined by two factors: the profit wedges in both industries as well as the input substitutability of the upstream producers.

Only a tax on pollution $\left(t^E\right)$ can bring in not only the downstream firms' input substitution effect but also the upstream firms' input substitution effect. The existence of the upstream firms' input substitutability strengthens the reason to tax pollution of the upstream industry, and subsidize the downstream industry, if $\left(p - c^Y\right) + \left(q - c^X - wD_E c_r^X\right) c_q^Y < 0$. Moreover, the upstream firms' input substitutability weakens the need to subsidize pollution of the upstream industry, if $\left(q - c^X - wD_E c_r^X\right) > 0$. If the size of environmental damages to welfare is greater than the upstream industry's profit but is smaller than the sum of both industries' profits (i.e., $\left(p - c^Y\right) + \left(q - c^X - wD_E c_r^X\right) c_q^Y < 0 < \left(q - c^X - wD_E c_r^X\right)$), then the first term in (3.40) remains negative while the second becomes positive. Meanwhile, the third term is always positive. In this case, the downstream firms' input substitutability, together with the upstream firms' input substitutability has power to change the direction of a tax reform from $t^E > 0$ and $t^Y < 0$ to $t^E < 0$ and $t^Y > 0$. Therefore, in my model where the distortion from pollution is simultaneously considered along with other distortions from imperfect competition in both industries, σ^Y cannot solely determine the direction of tax reforms in general. Only the profit wedges and the upstream firms' input substitutability can change the direction of tax reforms in general.

3.6 CONCLUSION

In this chapter, I have examined the welfare effects of various revenue-neutral tax reforms in the case of two vertically-separated oligopolies (downstream and upstream), where the upstream industry is polluting. My results have shown analytically when and how government can improve welfare by initiating various tax reforms, regardless of either the feasibility of a lump sum transfer or the availability of a tax on pollution.

The profit wedges that is the deffrence between the unit price and the unit cost and the marginal environmental damages (MED) becomes important deciding the direction of a tax reform. In general, if the MED is more damaging to social welfare than the marginalization problem due to under-production does, government should levy a tax on pollution (or on the intermediate good) and use this revenue to subsidize the downstream industry. On the other hand, if the environmental damages are less pressing, the direction of a tax reform should be reversed to the combination of a subsidy for pollution (or for the intermediate good) and a tax on the downstream output.

If the pollution problem is less severe than the upstream industry's marginalization problem but is more severe than the double marginalization problems in both industries, the direction of a tax reform can be determined only when informationameters is available. In this case, the downstream firms' input substitutability becomes important, because it weakens the upstream industry's market power. If it is strong enough, then the direction of a tax reform can be restored to a tax on pollution (or on the intermediate good) and a subsidy for the downstream output. A tax on the intermediate good has this input substitution effect by the downstream firms and, therefore, can be used as a corrective tax instrument even in vertically-separated oligopolies with a pollution problem.

However, a tax on pollution is superior to a tax on intermediate good, because the former always brings in positive welfare effect from the upstream firms' input substitutability, which a tax on intermediate good cannot provide. And if this input substitution effect by the upstream firms is strong enough, then the direction of a tax reform can be restored to a tax on pollution (or on the intermediate good) and a subsidy for the downstream output even if the relative size of industry profits to environmental damages alone does not give policy makers a clear-cut conclusion about the direction of a tax reform.

I have used some simplifying assumptions in my model to obtain the analytically tractable results. First, in order to analyze the upstream producers' input substitutability resulting from a tax on pollution, I have postulated the upstream cost function as a function of the full price of polluting the environment, which is assumed to be the sum of the hidden, internal price of using the environment as an input and a tax on pollution. And I have used a simplifying assumption that the relationship between these two prices is linear and that the implicit internal price for using the environment does not change as a tax on pollution is introduced. However, if these two price factors are related to each other, the results might turn out differently.

Second, I have nSecond, I have not examined the optimal taxation problem here since government does not have any revenue requirement in my model. But it would be more difficult to solve an optimal taxation problem, and it might be possible to derive closed form solutions only for some special cases.

Appendices

Appendix A

Appendix of Chapter 1

A.1 DERIVATION OF (1.19)

From the zero-profits condition,

$$p_Y F\left(L_Y,\ D\right) = L_Y + \left(1 + t_D\right) D\,. \tag{A1.1}$$

Totally differentiating it:

$$F\left(L_Y,\ D\right) dp_Y + p_Y\left(F_{L_Y} dL_Y + F_D dD\right) = dL_Y + \left(1 + t_D\right) dD + D dt_D\,.$$

Plugging the first-order conditions from the profit maximization into it:

$$Y dp_Y = D dt_D\,. \tag{A1.2}$$

Dividing the both sides of (A1.2) by p_Y gives (1.19).

A.2 HOW TO SOLVE THE SYSTEM OF EQUATIONS

From (1.22) and (1.23), the change in labor can be derived as follows:

$$\hat{L} = \left(\frac{\varepsilon}{1 - t_L - \varepsilon t_L}\right)\left[t_Y\left(\frac{Y}{L}\right)\hat{Y} + t_D\left(\frac{D}{L}\right)\hat{D}\right]. \tag{A2.1}$$

Defining the elasticity of substitution between two manufactured goods $\left(\sigma_Q\right)$ as $d\left(Y/X\right)/\left(Y/X\right)$ divided by $d\left(c_Y/p_X\right)/\left(c_Y/p_X\right)$, a behavioral equation can be obtained as follows:

$$\hat{Y} = \hat{X} - \sigma_Q \hat{c}_Y . \tag{A2.2}$$

Totally differentiate the household's budget constraint and use (1.19), (1.21), and (A2.2) to get:

$$\hat{X} = \hat{L} + \hat{w} + \phi\sigma_Q \hat{c}_Y , \tag{A2.3}$$

where $\phi \equiv (1+t_Y)Y \big/ (1-t_L)L$, which is the ratio of the consumer expenditure to a polluting manufactured good to the after-tax income from market labor.

Plug (A2.3) into (A2.2), then:

$$\hat{Y} = \hat{L} + \hat{w} - \sigma_Q (1-\phi)\hat{c}_Y . \tag{A2.4}$$

Defining the elasticity of substitution between inputs in production of Y (σ_Y) as $d\left(L_Y/D\right)\big/\left(L_Y/D\right)$ divided by $d\left(1/(1+t_D)\right)\big/\left(1/(1+t_D)\right)$, a behavioral equation can be obtained as follows:

$$\hat{L}_Y = \hat{D} + \sigma_Y \hat{t}_D . \tag{A2.5}$$

The first-order conditions from the profit maximization imply that $dY = dL_Y + (1+t_D)dD$. Thus, the percentage change in Y can be expressed as a weighted average of the percentage changes in the two inputs:

$$\hat{Y} = \left(\frac{L_Y}{Y}\right)\hat{L}_Y + (1+t_D)\left(\frac{D}{Y}\right)\hat{D}. \tag{A2.6}$$

Substitute (A2.5) into (A2.6) and use the zero-profits condition $Y = L_Y + (1+t_D)D$ at the initial equilibrium where all prices are one to get:

$$\hat{Y} = \hat{D} + \sigma_Y \left(\frac{L_Y}{Y}\right)\hat{t}_D. \qquad \text{(A2.7)}$$

The definition of the consumer price of Y is given $c_Y = p_Y + t_Y$. Totally differentiating it,

$$\frac{dc_Y}{c_Y} = \left(\frac{p_Y}{p_Y + t_Y}\right)\left(\frac{dp_Y}{p_Y}\right) + \frac{dt_Y}{p_Y + t_Y}.$$

Since $p_Y = 1$ (but $dp_Y \neq 0$) by assumption,

$$\hat{c}_Y = \left(\frac{1}{1 + t_Y}\right)\hat{p}_Y + \hat{t}_Y. \qquad \text{(A2.8)}$$

Substituting (1.19) into (A2.8):

$$\hat{c}_Y = \hat{t}_Y + \left(\frac{1 + t_D}{1 + t_Y}\right)\left(\frac{D}{Y}\right)\hat{t}_D. \qquad \text{(A2.9)}$$

Now, the equations (1.14), (1.15), (1.21), (1.23), (A2.2), (A2.3), (A2.5), (A2.6), and (A2.9) are a system of simultaneous equations that can be solved for the nine endogenous variables ($dU/\lambda L$, $\hat{t}_L$, $\hat{X}$, $\hat{Y}$, $\hat{D}$, $\hat{w}$, $\hat{L}$, $\hat{L}_Y$, and $\hat{c}_Y$) as functions of exogenous parameters and two exogenous policy variables, $\hat{t}_Y$ and $\hat{t}_D$. Then, for any particular policy experiment, one of these two tax rate changes will be set to zero in order to look at the effects of the other, where the change in revenue is offset by an adjustment in the labor tax t_L.

In order to solve the nine equations, they need to be reduced to fewer equations. To get the expression for the change in emissions $\left(\hat{D}\right)$, substitute (1.22) into (A2.4) and use (A2.1), and then:

$$\hat{Y} = \left\{ \frac{(1+\varepsilon)\, t_D \left(\dfrac{D}{L}\right)}{1-(1+\varepsilon)\left[t_L + t_Y \left(\dfrac{Y}{L}\right)\right]} \right\} \hat{D} - \left\{ \frac{\sigma_Q (1-\phi)\left[1-(1+\varepsilon)\, t_L\right]}{1-(1+\varepsilon)\left[t_L + t_Y \left(\dfrac{Y}{L}\right)\right]} \right\} \hat{c}_Y \,. \qquad \text{(B10)}$$

Equate (A2.10) with (A2.7) and use (A2.9) to get $\hat{D}$ in (1.24). For $\hat{Y}$ in (1.25), substitute (1.24) into (A2.7). Finally, for $\hat{L}$ in (1.26), substitute (1.24) and (1.25) into (A2.1).

A.3 THE LIST OF POLLUTING INDUSTRIES

- Coal Mining and Dressing
- Petroleum and Natural Gas Extraction
- Ferrous Metals Mining and Dressing
- Nonferrous Metals Mining and Dressing
- Nonmetal Minerals Mining and Dressing
- Logging and Transport of Timber and Bamboo
- Leather, Furs, Down and Related Products
- Timber Processing, Bamboo, Cane, Palm Fiber and Straw Products
- Furniture Manufacturing; Papermaking and Paper Products
- Petroleum Processing and Coking
- Raw Chemical Materials and Chemical Products
- Chemical Fiber; Rubber Products

- Plastic Products
- Nonmetal Mineral Products
- Smelting and Pressing of Ferrous Metals
- Smelting and Pressing of Nonferrous Metals
- Metal Products
- Transport Equipment
- Production and Supply of Electric Power, Steam and Hot Water
- Production and Supply of Gas.

Appendix B

Appendix of Chapter 3

B.1 DERIVATION OF EQUATION (3.12)

Since the aggregate demand $X = c_q^Y(q,\ w) \cdot Y(p,\ w)$ by Shepard's lemma, $X_q = c_{qq}^Y Y + c_q^Y Y_p \varphi_q$. Then, the elasticity of the derived demand for X is:

$$\varepsilon^X \equiv -\frac{qX_q}{X} = -\frac{q \cdot \left(c_{qq}^Y Y + c_q^Y Y_p \varphi_q\right)}{c_q^Y Y}. \tag{B1.1}$$

Rewrite it using $\varphi_q = \dfrac{c_q^Y}{\left(1-t^Y\right)G^Y}$ from (3.9) to get:

$$\varepsilon^X = -\frac{qc_{qq}^Y}{c_q^Y} - \frac{qc_q^Y Y_p}{\left(1-t^Y\right)G^Y Y}. \tag{B1.2}$$

Define the substitution elasticity between labor and intermediate good in downstream production as:

$$\sigma^Y \equiv -\frac{d\left(\dfrac{X^{DY}}{L^{DY}}\right)\Big/\left(\dfrac{X^{DY}}{L^{DY}}\right)}{d\left(\dfrac{q}{w}\right)\Big/\left(\dfrac{q}{w}\right)} = -\left(\frac{\dfrac{dX^{DY}}{X^{DY}} - \dfrac{dL^{DY}}{L^{DY}}}{\dfrac{dq}{q} - \dfrac{dw}{w}}\right), \tag{B1.3}$$

where X^{DY} and L^{DY} denote the input demands for the intermediate good and for labor by the downstream firm, respectively.

By Shepard's lemma, $X^{DY} = c_q^Y Y$ and $L^{DY} = c_w^Y Y$. Totally differentiate these to obtain $dX^{DY} = \left(c_{qq}^Y dq + c_{qw}^Y dw\right)Y$ and $dL^{DY} = \left(c_{wq}^Y dq + c_{ww}^Y dw\right)Y$, respectively. Therefore,

$$\frac{dX^{DY}}{X^{DY}} - \frac{dL^{DY}}{L^{DY}} = \frac{c_{qq}^Y dq + c_{qw}^Y dw}{c_q^Y} - \frac{c_{wq}^Y dq + c_{ww}^Y dw}{c_w^Y}. \tag{B1.5}$$

Since the cost function is homogeneous of degree one in $(q,\ w)$, $c^Y = c_q^Y q + c_w^Y w$ by Euler's formula. Differentiate it with respect to q and w to obtain:

$$c_{wq}^Y = -\frac{q}{w} c_{qq}^Y,$$

$$c_{ww}^Y = -\frac{q}{w} c_{qw}^Y = \left(\frac{q}{w}\right)^2 c_{qq}^Y, \tag{B1.6}$$

and

$$c_{wq}^Y = c_{qw}^Y.$$

Substitute the above expressions into (B1.5) to get:

$$\frac{dX^{DY}}{X^{DY}} - \frac{dL^{DY}}{L^{DY}} = \frac{q c_{qq}^Y \left(q c_q^Y + w c_w^Y\right)}{w c_q^Y c_w^Y}\left(\frac{dq}{q} - \frac{dw}{w}\right). \tag{B1.7}$$

Substitute (B1.7) into (B1.3) to get:

$$\sigma^Y = -\frac{q c_{qq}^Y c^Y}{w c_q^Y c_w^Y}. \tag{B1.8}$$

Simplify (B1.2) using (B1.8) to finally get (3.12).

Similarly, the substitution elasticity between E and L^X by the upstream industry can be obtained as follows:

$$\sigma^X = -\frac{r^0 c_{rr}^X c^X}{w c_r^X c_w^X}. \tag{B1.9}$$

B.2 DERIVATION OF EQUATION (3.26)

Substitute the definitions for CS, Π^X, and Π^Y into (3.22) to get:

$$\begin{aligned} W &= U(Y) - \frac{pY}{w} - D(E) \\ &+ \frac{\left[\left(1-t^X\right)q - c^X\right]c_q^Y Y + \left[\left(1-t^Y\right)p - c^Y\right]Y + T}{w}, \end{aligned} \tag{B2.1}$$

where $X = X(q,\ w) = c_q^Y(q,\ w)\cdot Y(p,\ w)$, $Y = Y(p,\ w)$, $c^X = c^X(r,\ w)$, $c_r^X = c_r^X(r,\ w)$, $c^Y = c^Y(q,\ w)$, $c_q^Y = c_q^Y(q,\ w)$, $p = p\left(t^X,\ t^Y,\ t^E\right)$, $q = q\left(t^X,\ t^Y,\ t^E\right)$, and $D = D(E) = D\left(c_r^X X\right) = D\left(c_r^X c_q^Y Y\right)$.

From (B2.1),

$$\frac{\partial W}{\partial t^X} = W_p \frac{\partial p}{\partial t^X} + W_q \frac{\partial q}{\partial t^X} - \frac{qX}{w}, \tag{B2.2}$$

$$\frac{\partial W}{\partial t^Y} = W_p \frac{\partial p}{\partial t^Y} + W_q \frac{\partial q}{\partial t^Y} - \frac{pY}{w}, \tag{B2.3}$$

and $$\frac{\partial W}{\partial t^E} = W_p \frac{\partial p}{\partial t^E} + W_q \frac{\partial q}{\partial t^E} - \frac{E}{w} - c_{rr}^X c_q^Y D_E Y \,, \tag{B2.4}$$

where $W_p \equiv \partial W/\partial p$, $W_q \equiv \partial W/\partial q$, and $c_{rr}^X \equiv \partial^2 c^X/(\partial r)^2$.

Substitute (B2.2), (B2.3), and (B2.4) into (3-25) and use $\sigma^X = -rc_{rr}^X c^X / wc_r^X c_w^X$ from (B1.9) to get:

$$\begin{aligned} dW = {} & \left(W_p \frac{\partial p}{\partial t^X} + W_q \frac{\partial q}{\partial t^X}\right) dt^X + \left(W_p \frac{\partial p}{\partial t^Y} + W_q \frac{\partial q}{\partial t^Y}\right) dt^Y \\ & + \left(W_p \frac{\partial p}{\partial t^E} + W_q \frac{\partial q}{\partial t^E} + \frac{\sigma^X c_w^X w D_E E}{r^0 c^X}\right) dt^E. \end{aligned} \tag{B2.5}$$

From (B2.1),

$$\begin{aligned} wW_p = {} & wU_Y Y_p - Y - pY_p - wc_r^X c_q^Y Y_p D_E \\ & + \left[\left(1-t^Y\right)p - c^Y\right] Y_p + \left(1-t^Y\right) Y + \left[\left(1-t^X\right)q - c^X\right] c_q^Y Y_p \\ = {} & \Pi^Y \frac{pY_p}{Y}\frac{1}{p} + \Pi^X \frac{pY_p}{Y}\frac{1}{p} - t^Y Y - wc_r^X c_q^Y Y \frac{pY_p}{Y}\frac{1}{p} D_E \\ = {} & -\frac{\varepsilon^Y \left(\Pi^X + \Pi^Y - wD_E E\right)}{p} - t^Y Y \end{aligned} \tag{B2.6}$$

and

$$wW_q = -wc_r^X c_{qq}^Y D_E Y - c_q^Y Y + \left(1-t^X\right)c_q^Y Y + \left[\left(1-t^X\right)q - c^X\right]c_{qq}^Y Y$$

$$= -wc_r^X c_q^Y \frac{c_{qq}^Y}{c_q^Y} D_E Y - t^X c_q^Y Y + \left[\left(1-t^X\right)q - c^X\right]c_q^Y \frac{c_{qq}^Y}{c_q^Y} Y \tag{B2.7}$$

$$= -\frac{\sigma^Y wc_w^Y \left(\Pi^X - wD_E E\right)}{qc^Y} - t^X X.$$

Plug (B2.6) and (B2.7) into (B2.5) and set $t^X = t^Y = t^E = T = 0$, then (3-26) is obtained.

B.3 DERIVATION OF EQUATION (3.31)

Totally differentiate (3-22) to get:

$$dW = \frac{\partial W}{\partial t^X} dt^X + \frac{\partial W}{\partial t^Y} dt^Y + \frac{\partial W}{\partial t^E} dt^E . \tag{B3.1}$$

Rewrite it using (3-30):

$$dW = \left(\frac{\partial W}{\partial t^X} - \frac{\partial W}{\partial t^Y}\frac{qX}{pY}\right)dt^X + \left(\frac{\partial W}{\partial t^E} - \frac{\partial W}{\partial t^Y}\frac{E}{pY}\right)dt^E . \tag{B3.2}$$

Substitute (B2.2), (B2.3), (B2.4) and (B1.9) into (B3.2), then (3-31) is obtained.

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